Physics 30

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Atomic Physics
Unit D

Physics 30

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Atomic Physics

Unit D

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Students	✓
Teachers	✓
Administrators	
Home Instructors	
General Public	
Other	

You may find the following Internet sites useful:

- Alberta Education, **http://www.education.gov.ab.ca**
- Learning Resources Centre, **http://www.lrc.education.gov.ab.ca**
- Tools4Teachers, **http://www.tools4teachers.ca**

Exploring the electronic information superhighway can be educational and entertaining. However, be aware that these computer networks are not censored. Students may unintentionally or purposely find articles on the Internet that may be offensive or inappropriate. As well, the sources of information are not always cited and the content may not be accurate. Therefore, students may wish to confirm facts with a second source.

Physics 30

Learn EveryWare

Investigating the Nature of the Atom

Module 7

Contents

Unit D Introduction

Unit Introduction

The universe is so large that distance needs to be measured relative to the speed of light. For example, a photon travelling 300 million metres per second would take 100 000 years to cross from one side of the Milky Way galaxy to the other. For that photon to travel across the universe would take approximately 93 billion years, according to current estimates. Considering this, you might think that a photon travelling for an entire year would cover a great distance; but on the scale of the universe, it would hardly appear to be moving at all. Knowing this helps you understand how small Earth and its inhabitants are relative to what some consider the infinitely large space of the universe. On this scale you wouldn't even know Earth existed, let alone be able to find it.

Humans have learned all of this by looking outward at larger things beyond the familiar surroundings of the planet Earth. Now imagine what humans could learn by looking inward at smaller and smaller scales. Can you look inward as far as you can look outward? If you could, what would you see and find? These are deep questions. Consider the journey inward as it is illustrated below, as you zoom in from the universe to the level of a subatomic particle.

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Using extensive technology and observations, humans have learned that the universe comprises vast amounts of matter, with only about 4% of it visible in stars and gas clouds.

With less powerful technology, the solar system is observable. It occupies an infinitesimally small place relative to the universe and is composed of various planets orbiting a single star.

Looking inside the solar system, Earth is just one of many planets.

Earth is surrounded by a very thin atmosphere.

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Inside the atmosphere and near Earth's surface, there is an abundance of gas, liquid, and solid matter.

Viewed up-close using only the human eye, water can be seen collecting at the end of a leaf.

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Because of extensive technology and experimentation, the water at the end of the leaf is known to be composed of many small molecules.
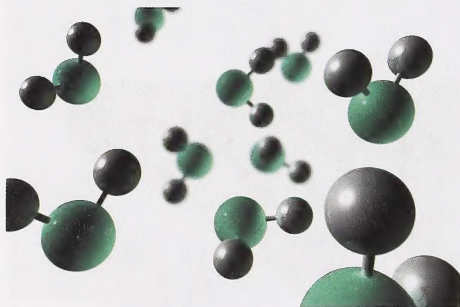
Each water molecule, in turn, is composed of smaller components called atoms.

© Sai Yeung Chan/shutterstock
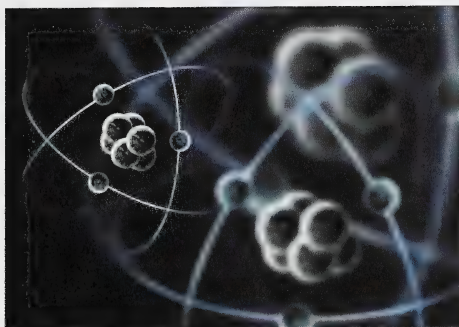
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With even more extensive technology and theoretical knowledge, scientists have determined that the atom comprises smaller particles, called electrons, protons, and neutrons.

Looking even deeper, scientists have found that the protons, electrons, and neutrons are, in turn, made of even smaller particles called quarks.

?
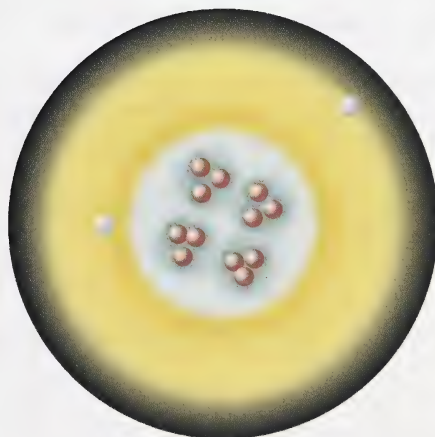
Is there any reason we can't look deeper? Is there any reason to suspect that quarks are, in turn, made of something smaller?

In Unit D you will investigate atomic physics. You may have noticed that the molecules, atoms, and subatomic particles are illustrations instead of photos. It is important to know that, where reasonable, these illustrations only show an artistic impression of models and theories that are used to describe complex ideas; they do not necessarily provide an accurate representation of the reality. Recall from Module 6: Lesson 3 that a microscope's magnification is limited by the size of the wavelength (or de Broglie wavelength) used to produce the image. To study atomic physics at a scale beyond the resolving power of any microscope (matter or optical), new tools, theories, models, and technology need to be deployed.

In Module 7 you will look at the experiments that established quantum theory. You will see how J.J. Thomson's charge-to-mass ratio of the electron established proof that the atom is not the smallest particle of matter and led to a new model of the atom. You will see how Millikan used an electric field apparatus to measure the charge on an individual electron, and how the results of Rutherford's alpha particle scattering from gold foil shocked him and led to our understanding of the nucleus of the atom. Finally you will look at Bohr and how spectroscopy of hydrogen gas led to the establishment of the Bohr model of the atom to unify the experimental data of the time into a model of the atom.

In Module 8 you will see how modern physics has developed. You will learn about the nuclear reactions of fission and fusion, how to write the nuclear equation, how the rate of nuclear reactions allows us to determine the products and age of a sample, how nuclear reactions have led to the discovery of more and more subatomic particles, and the theory to describe the atom.

In this unit you will discover how experimental evidence has been gathered and interpreted to build an understanding of how the atom is organized. By the end of this unit you will understand the electrical nature of the atom and the quantization of energy in the atom and nucleus. You will also understand the application of this knowledge in technologies related to nuclear energy, atomic research, and nuclear imaging.

Essential Questions

- What is the electrical nature of the atom?

- How is it possible to investigate the nature of the atom?

- What experimental evidence supports the theory that energy is quantized in atoms and nuclei?

- How has the knowledge of atomic and subatomic structure been utilized in the development of new technology?

The Structure of Matter

for the

**is defined
by the**

**nuclear fission and fusion and
the ongoing development of the standard model**

**electrical nature of the atom and the
quantization of energy in atoms and the nuclei**

in applications, these concepts help to understand
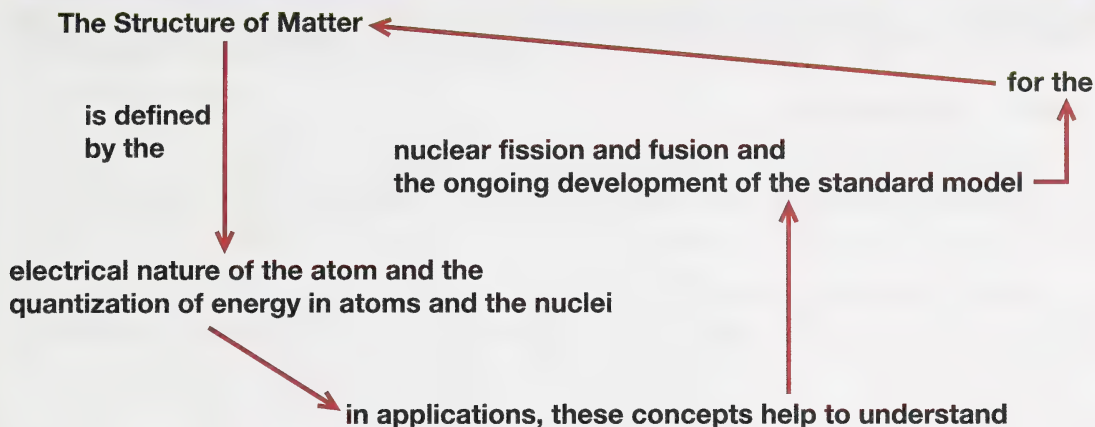
Module Descriptions

Module 7—Investigating the Nature of the Atom

In Module 7 you will investigate the electrical structure and quantum nature of the atom.

As you are working in Module 7, keep the following question in mind:

- How does the quantization of energy in atoms and nuclei reveal the electrical nature of the atom?

Module 8—Nuclear Decay, Energy, and the Standard Model of the Atom

In Module 8 you will investigate nuclear decay, energy, and the standard model of the atom.

As you are working in Module 8, keep the following question in mind:

- What is our current understanding of the atom and how do models, such as the standard model, evolve as new evidence and technology are applied at the atomic and subatomic levels?

Module Introduction

In this module you will explore the early investigations related to the structure of matter. From investigations with cathode rays to the interaction of electromagnetic radiation and matter, these early experiments laid the foundation for our current understanding of the structure of matter.

The discovery of the electron and nucleus, as well as their physical characteristics, was critical to building an understanding of how the atom is modelled and organized. At the end of Module 7 you will understand the electrical nature of the atom and the quantization of energy in the atom and nucleus.

Specifically, you will be asked to apply your knowledge to answer the following question:

- How does the quantization of energy in atoms and nuclei reveal the electrical nature of the atom?

Big Picture
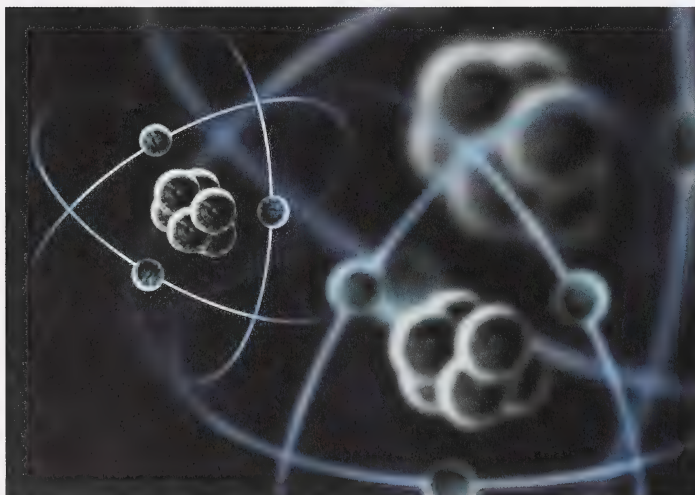
© James Thew/shutterstock

In this artistic representation of the atom, you can see smaller particles orbiting along what appear to be circular paths that enclose a chunky nucleus made up of many smaller particles. Is this really what an atom looks like? Perhaps a better question would be this: Can an atom even be seen? If it could be seen, what would it look like?

Logically, the last question may seem pointless if the answer to the one before it is no.

What is more important, however, is that you understand how the atom is organized so you can predict how it will interact with its environment. And since the atom is too small to see or interact with, a model is used to help bring meaning to the physical reality. Scientists have been working with models of the atom for some time, probing its internal structure and electrical nature. This work has led to the ongoing development of valuable technologies, such as the mass spectrometer, which can identify unknown atoms and elements based on charge and mass.

By the end of Module 7 you will understand how current models of the atom can be applied in technologies used to explore the chemistry of the Earth, the Sun, and other planets in our solar system. You will also see how the practice of science plays out within the social context of the scientific community. You will investigate the nature of the atom.

As you are working in Module 7, keep the following questions in mind:

- How did the cathode ray contribute to the development of atomic models?

- How did J. J. Thomson determine the charge-to-mass ratio of an electron?

- How did Millikan discover the charge of an electron and how did this elementary charge inform models of the atom?

- What did Rutherford's scattering experiment suggest about the nature of the nucleus? How did it lead to the planetary model of the atom?

- What is the Bohr model of the atom? How are the concepts of stationary states and energy quantization used to explain how a gas absorbs and emits only certain wavelengths of electromagnetic radiation?

Module Assessment

Each lesson has a teacher-marked assignment, based on work completed in the lesson. In addition, you will be graded on your contributions to the Discuss section of each lesson.

You will also be asked to complete Self-Check or Try This questions, which you should place in your Physics 30 course folder. These are not formally assessed, but they are a valuable way to practise the concepts and skills of the lesson. These activities can provide you with reflective feedback on your understanding of the lesson work.

You will be marked for your lesson work on the following items:

- Module 7: Lesson 1 Assignment
- Module 7: Lesson 2 Assignment
- Module 7: Lesson 3 Assignment

At the end of the module you will complete a module assessment that consists of two Diploma Exam-style written-response questions. The first question will assess your knowledge of charge-to-mass ratios and the second question will assess your knowledge of electromagnetic induction. See the Module Summay and Assessment section towards the end of this booklet for more information.

In This Module

Lesson 1—Cathode Rays and Thompson's Experiment

In this lesson you will learn about the discovery of the electron and its charge-to-mass ratio. You will explore early experiments with cathode ray tubes and the applications of such technologies in modern mass spectrometers.

You will investigate the following essential questions:

- How did the cathode ray contribute to the development of atomic models?
- How did J. J. Thomson determine the charge-to-mass ratio of an electron?
- How did Thomson's experiment contribute to science and technology?

Lesson 2—The Millikan Experiment

In this lesson you will learn about Millikan's oil drop experiment and how he determined the elementary charge of an electron using scientific judgment.

You will investigate the following essential questions:

- How were Millikan's experimental design and apparatus applied to determine the charge of a single electron?

- How did the new fundamental quantity, the elementary charge, inform models of the atom?

- Why did Millikan's use of scientific judgment cause a controversy among other scientists and scholars?

Lesson 3—The Rutherford and Bohr Models of the Atom

In this lesson you will explore information about the atom revealed by its interaction with electromagnetic radiation and with charged particles.

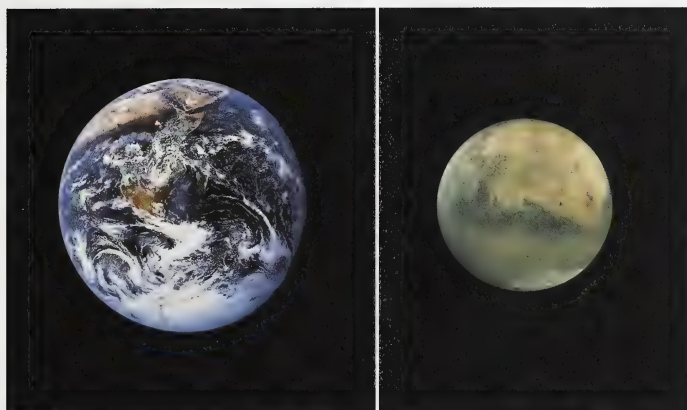You will investigate the following essential questions:

- What does Rutherford's scattering experiment suggest about the nature of the nucleus, and how did it lead to the planetary model of the atom?

- What is the Bohr model of the atom? How is the concept of stationary states and energy quantization used to explain how a gas absorbs and emits only certain wavelengths of electromagnetic radiation?

Lesson 1—Cathode Rays and Thomson's Experiment

Get Focused

Scientists believe that Earth's early atmosphere was similar to the atmosphere that currently exists on Saturn's moon Titan. Presumably, this could give rise to conditions that may support life on Titan. It is a unique moon—the only one known to have a fully developed atmosphere with more than just trace gases.

In fact, the atmosphere is so thick and the gravity so low that you could fly through it by flapping wings attached to your arms! It is

Spacescapes/Getty Images

98.4% nitrogen and 1.6% methane, and it appears as thick orange smog due to reactions caused by ultraviolet radiation and methane in the upper atmosphere. How is it possible to know such complex details about a place that can't even be seen with the naked eye?

The European Space Agency, in conjunction with NASA and the Italian Space Agency, successfully landed the Huygens probe on the surface of Titan on January 14, 2005. The proble had enough power to function during its two and one-half hour descent to the surface and for more than 90 minutes while on the surface. During that time the probe used a mass spectrometer to measure the molecular mass of the gases in the atmosphere and then sent that data back to Earth for analysis.

The molecular mass data from the probe was used to identify and confirm the type of chemicals that make up the moon's atmosphere. Ironically, this snapshot of data, collected halfway across the solar system, was made possible by the very close examination of the infinitely small. To be precise, the mass spectrometer is a technology that was born from a similar quest for information, a quest that focused on the composition of matter and, in particular, the discovery of the electron. Approximately 105 years before the Huygens probe touched down on Titan, the electron and its characteristics were about to be discovered using similar technology.

In Lesson 1 you will learn about the discovery of the electron and its charge-to-mass ratio. You will explore early experiments with cathode ray tubes and the applications of such technologies in modern mass spectrometers.

In this lesson you will answer the following essential questions:

- How did the cathode ray contribute to the development of atomic models?
- How did J. J. Thomson determine the charge-to-mass ratio of an electron?
- How did Thomson's experiment contribute to science and technology?

Module 7: Lesson 1 Assignment

Your teacher-marked Module 7: Lesson 1 Assignment requires you to submit responses to the following questions:

- Assignment—A 1, A 2, A 3, A 4, A 5, A 6, and A 7
- Reflect and Connect—RC 1

The other questions in this lesson are not marked by the teacher; however, you should still answer these questions. The Self-Check and Try This questions are placed in this lesson to help you review important information and build key concepts that may be applied in future lessons.

After a discussion with your teacher, you must decide what to do with the questions that are not part of your assignment. For example, you may decide to submit to your teacher the responses to Try This questions that are not marked. You should record the answers to all the questions in this lesson and place those answers in your course folder.

Explore

Cathode Rays

All the technology needed to find the electron was available near the end of the 19th century. The manufacturing of sealed glass instruments and tubes had reached a quality that could support low-pressure environments with the operation of a vacuum pump. Around 1850 Heinrich Geissler invented a pump that could produce extremely low pressures. He shaped glass into a tube and evacuated the air from within. Then he filled the tube with a low-density, pure gas. When a potential difference was applied to the electrodes at either end of the tube, a colourful electrical discharge was produced. Further observations indicated that different types of gas emitted a unique and characteristic colour. Geissler called these tubes gas discharge tubes.
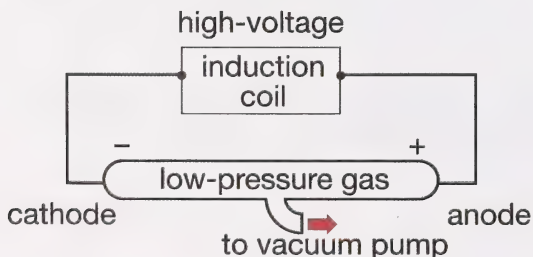
This diagram is an illustration of a simple gas discharge tube.

Immediately, the **cathode ray** became the subject of intense experimentation.

cathode ray: a free electron emitted by a negative electrode in a low-pressure environment

William Crookes proved that the emissions travelled from the cathode to the anode. For this reason, gas discharge tubes are sometimes called Crookes tubes or, more commonly, cathode ray tubes (CRT). Crookes placed a paddle wheel, which was free to rotate, in the path of the cathode rays.

When the rays hit the paddles, they caused the wheel to move along a track inside the tube. This proved that cathode rays were composed of moving particles that had mass and momentum and were capable of doing work.
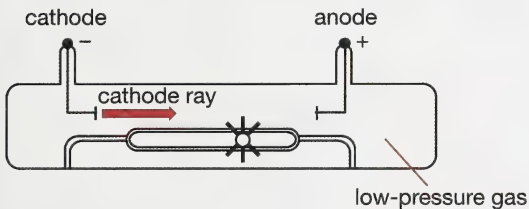
Crookes also demonstrated that cathode rays are deflected by a magnetic field. Using the left-hand rule for moving electric charges in a magnetic field, he proved that the particles were negatively charged and were emitted by the cathode.
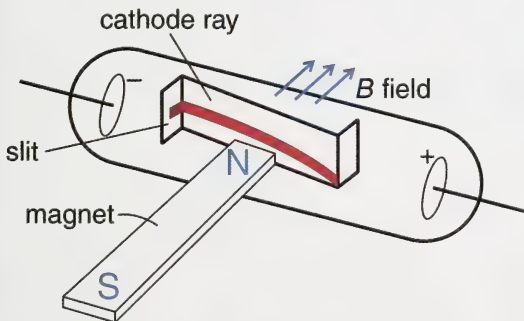
Arthur Schuster used a set of external charged plates to demonstrate that the cathode rays were affected by electric fields. The direction of deflection of the cathode rays further proved that they were, in fact, negative.
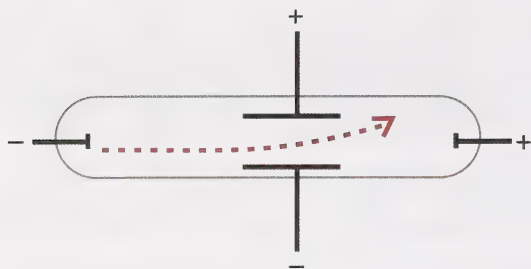
Based on these observations, cathode rays

- travel from the negative electrode to the positive electrode
- travel in straight lines and cause shadows
- have momentum and energy to do work
- are deflected by magnetic and electric fields and have a negative charge

Read

Read "Cathode-ray Experiments" on pages 754 to 755 of your physics textbook. What was the evidence that the cathode rays were particles with charge and mass?

Module 7: Lesson 1 Assignment

Go to the Module 7 Assignment Booklet, and complete question A 1.

The Thomson Experiment

In 1897 J. J. Thomson attempted to measure both the mass and charge of the negative particles making up the cathode ray. He was unable to measure either the charge or mass by itself, but he was able to measure them both as a ratio. In other words, he designed an experiment to determine the amount of charge per unit of mass for the particles in the cathode ray. The design of his experiment is based on electric and magnetic forces that act on charged particles. Recall the equations and hand rules that describe these forces.

An electrical force can deflect the charged particles in the cathode ray.

$$\vec{F}_e = q\vec{E}$$

Electric Field Deflector

electron gun

heater

cathode

anode

cathode rays

horizontal
deflection
plates

vertical
deflection
plates
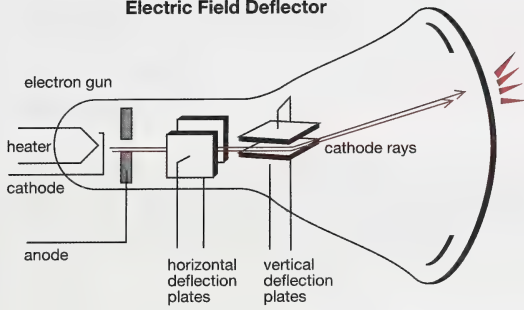
A magnetic force can deflect charged particles in a cathode ray.

$$\left|\vec{F}_m\right| = qv_\perp B$$

Magnetic Field Deflector

cathode

magnetic field

anode
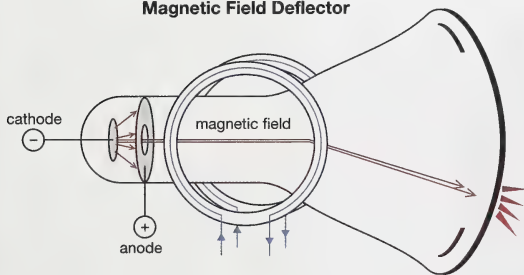
The direction of the force depends on the type of charge and the direction of the electric field. For example,

$\vec{E}$

$\vec{F}$ $\vec{v}$

$\vec{F}$

$\vec{E}$

$\vec{v}$
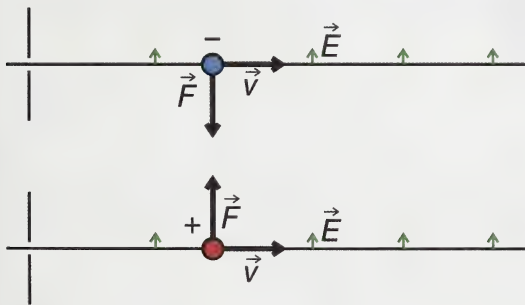
The direction of the force is determined using hand rules. For example,

F

v

B
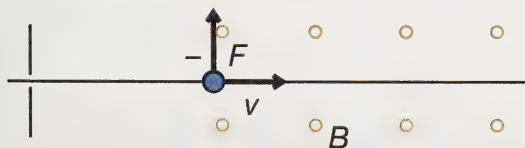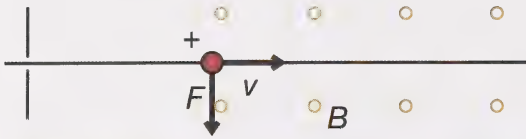
Recall: In the open palm left-hand rule for negative charges, the thumb goes in the direction of movement ($\vec{v}$), the fingertips go in the direction of the magnetic field (out of the page in this case), and the palm points in the direction of the force on the charge.
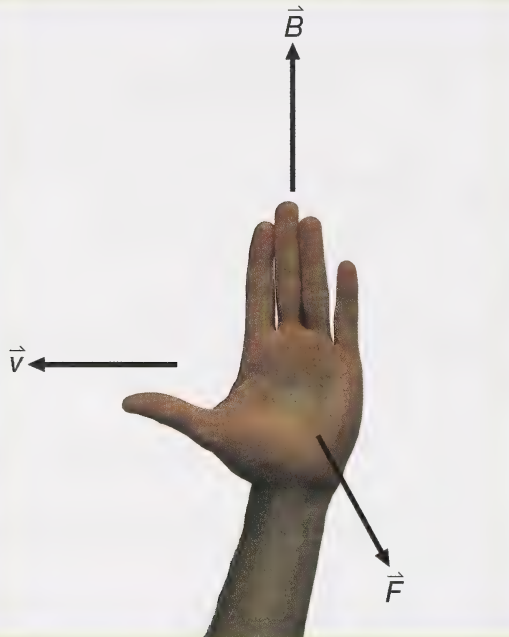
Equation 1

Using only these two forces, Thomson designed an experiment that consisted of two basic investigations. First, he used his apparatus to determine the speed of a cathode ray particle in the tube; then, knowing the speed, he used the apparatus to determine the charge-to-mass ratio of the particle.

$$\vec{F}_{\mathrm{m}} = \vec{F}_{\mathrm{e}}$$
$$\cancel{q}v_{\perp}\vec{B} = \left|\vec{E}\right|\cancel{q}$$
$$v_{\perp} = \frac{\left|\vec{E}\right|}{\vec{B}}$$

Part 1: Determining the Speed of a Cathode Ray Particle

A magnetic field or an electric field acting alone will deflect a charged particle that is travelling perpendicularly to it.

Thomson used this knowledge to determine the speed of a travelling particle using both a magnetic and electric field simultaneously. He set up the apparatus in such a way that the electric force was oriented opposite to the magnetic force. This way, if the magnetic force were equal in magnitude to the electric force, the particle would travel straight through the apparatus. When the particle travels straight through, Equation 1 can be used to calculate its speed.

Self-Check

SC 1. A beam of electrons is fired to the right into a set of perpendicular electric and magnetic fields. The electric field is oriented downward and the magnetic field is into the page.

   a. Explain the direction of the electric force acting on the electrons.
   b. Explain the direction of the magnetic force acting on the electrons.
   c. If the electrons travel undeflected, draw a free-body diagram of the electrons.

SC 2. A particle travels undeflected (straight) through a Thomson apparatus that has a magnetic field of 2.0 T and an electric field of 100 V/m oriented perpendicularly to one another. Use Equation 1 to determine how fast it is travelling. Show your work. Verify your answers by going to the Physics 30 Multimedia DVD and using the "Thomson's Charge/Mass Measurement Simulation." Set the calculated velocity, magnetic field, and electric field as stated. You should observe that the particle travels undeflected through the apparatus if your velocity calculation is correct. Note that the applet will take a few minutes to load.

Check your work with the answers in the Appendix.

Watch and Listen

Go to the Physics 30 Multimedia DVD and open "Determining Charge-to-Mass Ratio (Thomson's Charge/Mass Measurement)" to see how Thomson used magnetic and electric fields to determine the charge-to-mass ratio of a particle.

Try This

SIM 1. Go to the Physics 30 Multimedia DVD and open the "Thomson's Charge/Mass Measurement Simulation" again.

Adjust the speed slider to match your answer from SC 1.

Speed: 150.0 m/s

Note: The applet reset button changes all of the sliders, so you must adjust them all before repeating the experiment. Notice the difference in the electron's path if you try different speeds. Predict what the path will be if you change the charge or mass of the particle. Verify your prediction by changing the charge and mass.

This arrangement with a crossed (perpendicular) pair of uniform electric and magnetic fields is called a velocity selector. If charged particles with a variety of velocities enter the fields, only those whose velocity is perpendicular to both fields and whose speed satisfies $v = \dfrac{|E|}{B}$ will continue in a straight line. The set-up is, therefore, able to select charged particles of a given velocity from all other particles by setting the fields to appropriate values. Velocity selectors have an application in mass spectrometers.

The arrangement can also be used to measure the speed of charged particles. One must adjust the electric and magnetic fields until there is no deflection and then use the equation to solve for the speed. It is important to note that the value of the speed for which there is no deflection depends on neither the charge nor the mass of the particle. Therefore, you can use a velocity selector to measure the speed of charged particles even if you do not know their charge or their mass.

Read

Read "Charge-to-mass Ratio of the Electron" on page 755 of your physics textbook.

Part 2: Determining the Charge-to-Mass Ratio of a Cathode Ray Particle

Having determined the speed of the particles as they are coming from the source, you now have to perform a second experiment to determine the charge-to-mass ratio. In the second experiment the particles go through the same apparatus, but with one of the fields turned off. In this circumstance one field will deflect the particles because there is no other force from the other field to balance it.
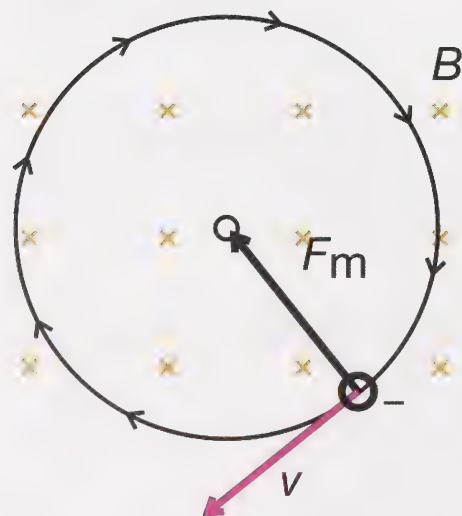
Recall that a magnetic force will produce a perpendicular force on a moving charge as determined by the hand rule. The uniform perpendicular force will cause the charged particle to move along a circular path of constant radius. Therefore,

$$F_{inward} = F_m$$

Given the definitions of the inward, centripetal force and the magnetic force, it is possible to derive an equation for the charge-to-mass ratio of the particle exhibiting circular motion in the magnetic field alone.

$$F_{inward} = F_m$$
$$\frac{mv^2}{r} = qvB$$
$$\frac{q}{m} = \frac{v}{Br}$$

In a Thomson-style experiment, the velocity is first determined using both a known magnetic and electric field. Then, by turning off the electric field and measuring the radius of the circular path made by the charged particles, you would be able to determine the charge-to-mass ratio of the particles.

Thomson determined that the charge-to-mass ratio of the particles in a cathode ray was 1.76×10^{11} C/kg. This value was unique to all cathode rays regardless of the metal electrodes used to produce them. Thomson had discovered the electron, but, more importantly, he had determined that the charge-to-mass ratio for an electron was thousands of times larger than that of a hydrogen ion, which meant that the electron was a "subatomic" particle. He proposed a radical idea at the time—the atom was divisible into smaller particles. And since no positive subatomic particles had been discovered at the time, he suggested that the atom consisted of electrons embedded in a blob of massless positive charge, what is now known as the raisin-bun model of the atom. You will learn more about this model later on in the lesson.

Read

Read "Determining Charge-to-mass Ratios" on pages 757 to 758 of your physics textbook.

Self-Check

SC 3. Using the charge and mass values on your physics data sheet, what is the charge-to-mass ratio of

a. the proton
b. the alpha particle
c. the neutron

SC 4. How many times larger is the charge-to-mass ratio of the electron than the proton?

Check your work with the answers in the Appendix.

In order to obtain the charge and mass values on the physics data sheet, experimental data was analyzed. Here are some examples of how that can be done.

Example Problem 1. A charged particle is travelling horizontally at 3.60×10^6 m/s through a vertical magnetic field of 0.710 T. If the radius of the curvature of the particle's path is 0.950 m, what is the charge-to-mass ratio of the particle?

Given

$$v = 3.60 \times 10^6 \text{ m/s}$$
$$\left| \vec{B} \right| = 0.710 \text{ T}$$
$$y = 0.950 \text{ m}$$

Required

the charge-to-mass ratio of the given particle

Analysis and Solution

$$\left| \vec{F_m} \right| = \left| \vec{F_c} \right|$$
$$q v_\perp \left| \vec{B} \right| = m \left| \vec{a_c} \right|$$
$$q v_\perp \left| \vec{B} \right| = m \frac{v^2}{r}$$
$$\frac{q}{m} = \frac{v}{\left| \vec{B} \right| r}$$
$$= \frac{\left(3.60 \times 10^6 \text{ m/s} \right)}{(0.710 \text{ T})(0.950 \text{ T})}$$
$$= 5.34 \times 10^6 \text{ C/kg}$$

Paraphrase

The charge-to-mass ratio of the particle is 5.34×10^6 C/kg.

Example Problem 2. What is the speed of an electron that passes through an electric field of 6.30×10^3 N/C and a magnetic field of 7.11×10^{-3} T undeflected? The two fields are perpendicular to each other and to the path of the electron. What is the kinetic energy of the electron?

Given

$$\left| \vec{E} \right| = 6.30 \times 10^{-3} \text{ N/C}$$
$$\left| \vec{E} \right| = 7.11 \times 10^{-3} \text{ T}$$

Required

the kinetic energy of the electron

Analysis and Solution

Find the velocity by balancing the force magnetic with the force electric.

$$\left|\overrightarrow{F_m}\right| = \left|\overrightarrow{F_e}\right|$$

$$qv_\perp\left|\overrightarrow{B}\right| = \left|\overrightarrow{E}\right|q$$

$$v_\perp = \frac{\left|\overrightarrow{E}\right|}{\left|\overrightarrow{B}\right|}$$

$$= \frac{6.30\times10^3 \text{ N/C}}{7.11\times10^{-3} \text{ T}}$$

$$= 886\ 075.\overline{94} \text{ m/s}$$

Find the kinetic energy.

$$E_k = \frac{1}{2}\ mv^2$$

$$= \frac{1}{2}\left(9.11\times10^{-31} \text{ kg}\right)\left(886\ 075.\overline{94} \text{ m/s}\right)^2$$

$$= 3.576\ 269\ 83\times10^{-19} \text{ J}$$

Paraphrase

The kinetic energy of the electron is 3.58×10^{-19} J.

Try This

TR 1. An alpha particle travels through a magnetic field of 0.422 T perpendicular to the field. If the radius of arc of the deflected particle is 1.50×10^{-3} m, what was the speed of the alpha particle? (3.05×10^4 m/s)

TR 2. A proton travels through a magnetic field at a speed of 5.40×10^5 m/s, perpendicular to the field. If the radius of curvature is 7.20 mm, what is the magnetic field strength? (0.783 T)

TR 3. Alpha particles travel undeflected through magnetic and electric fields that are perpendicular to each other. If the speed of the alpha particles was 7.80×10^5 m/s and the magnetic field strength was 0.220 T, what was the electric field strength? (1.72×10^5 N/C)

Module 7: Lesson 1 Assignment

Go to the Module 7 Assignment Booklet, and complete A 2, A 3, A 4, and A 5.

Watch and Listen

Thomson's experiment was about more than just finding the electron; it was also about understanding that matter could be divided into smaller parts. Go to the Physics 30 Multimedia DVD and watch the video "The Millikan Experiment" to see the glow emitted by a cathode ray tube, Thomson's apparatus, and hear about his groundbreaking work, which effectively demonstrated that the atom was made of divisible parts.

Self-Check

SC 5. Explain how Thomson calculated the unique charge-to-mass ratio for an electron by completing the following statements and equations.

Step 1: Determine the velocity of the electrons by measuring the_____ and _____ fields and using this equation:

_____

Step 2: Turn off the _____ field, leaving only the _____ field, which acts perpendicularly to the velocity of the charged particle. In this orientation the magnetic force causes the charged particle to exhibit _____ motion, giving the following expression for the charge-to-mass ratio:

_____

Check your work with the answers in the Appendix.

Reflect and Connect

One of the most practical uses for Thomson's ideas is the mass spectrometer like the one used on the Huygens space probe.
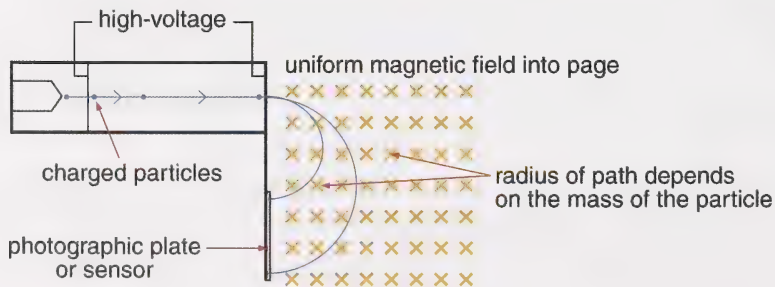
A very large voltage accelerates charged particles. The particles are directed into a magnetic field that is perpendicular to their velocity. Accordingly, a magnetic force is exerted perpendicular to the velocity and the particle travels in a circular path until it hits a photographic plate.

According to the equations that describe a magnetic force that causes circular motion, the radius of the circular path is dependent upon the mass of the particle; therefore, mass can be measured indirectly using the radius of the circular paths.

$$F_{inward} = F_m$$

$$\frac{mv^2}{r} = qvB$$

A mass spectrometer is a powerful application of Thomson's experiment. In addition to helping humankind explore the chemical composition of other planets and moons,

$$m = \frac{qBr}{v}$$

it can be used to identify, by charge and mass, biological chemicals such as toxins, steroids, and drugs. It also has extensive application in pharmaceutical research and quality control in chemical manufacturing.

Module 7: Lesson 1 Assignment

Go to the Module 7 Assignment Booklet and complete A 6 and RC 1.

Thomson's Raisin-bun Model

When Thomson started his charge-to-mass ratio experiments, the current atomic model was Dalton's indivisible billiard ball model. Dalton determined that each element had a unique atom, and from this he inferred that it was impossible to break matter down further. Thomson's experiment showed that the electron was much smaller than the smallest atom, a hydrogen atom.

Therefore, Thomson determined that an atom was indeed divisible and must consist of a solid, positively charged mass—the bun—with small, negatively charged electrons embedded in it—the raisins. This explained how a cathode ray tube was able to generate a beam of negatively charged cathode rays—electrons—from any metal. This was the first model of the atom that identified positive and negative charges as divisible parts of the atom.

Dalton atom
indivisible
"billiard ball"
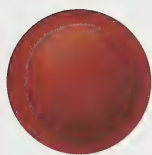
Thomson atom
divisible
"raisin bun"

positively charged
"bun"

negatively charged
electron "raisins"
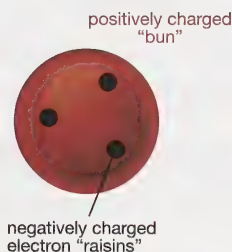
Self-Check

SC 6. The Dalton model of the atom, developed from chemistry experiments, indicated that the atom was indivisible. Why was J. J. Thomson able to state confidently that electrons were a component of the atom?

SC 7. Why did J. J. Thomson introduce the positively charged "bun" when he didn't calculate its charge-to-mass ratio?

Check your work with the answers in the Appendix.

Module 7: Lesson 1 Assignment

Go to the Module 7 Assignment Booklet and complete A 7.

Lesson Summary

In this lesson you focused on the following questions:

- How did the cathode ray contribute to the development of atomic models?
- How did J. J. Thomson determine the charge-to-mass ratio of an electron?
- How did Thomson's experiment contribute to science and technology?

Early work with vacuum tubes and electric potential led to the discovery of the cathode ray, which served as a vehicle for investigations into the nature of the particles that produced it. Experimentation and observations of cathode rays indicated that they were negatively charged particles capable of being deflected by magnetic and electric fields, and that they possessed the particle characteristics of kinetic energy and momentum.

Using the cathode ray, J. J. Thomson determined the charge-to-mass ratio of the particles by first measuring their speed with perpendicular electric and magnetic fields, and then by using only a magnetic field to produce uniform circular motion. Knowing the strength of the magnetic field, the velocity of the particles and the radius of the circular path they followed in the magnetic field, Thomson concluded that the unique charge-to-mass ratio for all cathode ray particles is 1.76×10^{11} C/kg, a ratio thousands of times larger than that for other common particles, such as the hydrogen ion.

Thomson's discovery of the electron's charge-to-mass ratio meant that the atom was indeed divisible into much smaller parts. Using this idea, he proposed the raisin-bun model of the atom in which negative charges are embedded in a blob of positive charge. Although this model is now known to be incorrect, it was the first model that identified positive and negative charges as divisible parts of the atom.

The concepts and theories used in Thomson's original experiment are now commonly applied in mass spectrometer technology. This technology can be used to identify unknown chemicals by comparing the unique charge-to-mass ratio of the unknown to the charge-to-mass ratio of other known compounds.

Lesson Glossary

cathode ray: a free electron emitted by a negative electrode in a low-pressure environment

Lesson 2—The Millikan Experiment

Get Focused

This photo, dating back approximately 100 years, shows the lab bench and equipment of physicist Robert Andrews Millikan. Together with his graduate student, Harvey Fletcher, Millikan used the large, black vessel visible on the table to measure a fundamental quantity, one that is related to all the matter in the universe—the elementary charge of an electron!

Inside that vessel, Millikan determined the elementary charge of an electron and, in conjunction with Thomson's work, he also determined its mass! How was it possible to measure the charge of an electron using a little bit of oil and two electric plates inside a sealed container?

In Lesson 2 you will learn about Millikan's oil drop experiment and how he determined the elementary charge of an electron.

In this lesson you will answer the following essential questions:

- How were Millikan's experimental design and apparatus applied to determine the charge of a single electron?

- How did the new fundamental quantity, the elementary charge, inform models of the atom?

- Why did Millikan's use of scientific judgment cause a controversy among other scientists and scholars?

Module 7: Lesson 2 Assignment

Your teacher-marked Module 7: Lesson 2 Assignment requires you to submit responses to the following:

- Lab—LAB 1
- Assignment—A 1, A 2, A 3, A 4, and A 5
- Discuss—D 1

The other questions in this lesson are not marked by the teacher; however, you should still answer these questions. The Self-Check and Try This questions are placed in this lesson to help you review important information and build key concepts that may be applied in future lessons.

After a discussion with your teacher, you must decide what to do with the questions that are not part of your assignment. For example, you may decide to submit to your teacher the responses to Try This questions that are not marked. You should record the answers to all questions in this lesson and place those answers in your course folder.

Explore

The Millikan Experiment

Shortly after Thomson confirmed the existence of the electron with a charge-to-mass ratio, physicist Robert Millikan designed and performed an experiment to determine the charge on an electron. His well-known oil drop experiment involved spraying tiny oil droplets into a vertical chamber with two metal plates on either end. The oil droplets became charged in the spraying process and when they entered the chamber, they began to fall under the influence of gravity. Millikan could then stop the free-falling droplets and reverse their direction of motion by applying a voltage across the two metal plates. Using a microscope and a timer, he measured the velocity of a single oil droplet in the electric field in order to determine the electrical force acting on it. This allowed him to determine the charge on the oil droplet, since

$$q = \frac{\vec{F_e}}{\vec{E}}$$

It is important to recognize that the charge on the oil droplet was likely due to the presence of many, many extra electrons. Therefore, the charge of an oil droplet will be an integer multiple of the charge on a single electron. Do not confuse the charge of the oil droplet with the elementary charge of a single electron.

How could Millikan determine the charge of a single electron using the charge on multiple oil droplets? By measuring the charge of many droplets and comparing them, he reasoned that the smallest difference in charge among all the droplets would be due to the presence of one extra electron. That small difference in charge would then be equal to the charge of a single electron or the elementary charge. Using the charge on numerous oil droplets and through careful analysis, Millikan discovered that the charges of the oil droplets were always integer multiples of 1.602×10^{-19} C.

He reasoned this must be the charge of a single electron, a value that is referred to as the **elementary unit of charge**.

elementary unit of charge: the charge of an electron or a proton, 1.60×10^{-19} C

Watch and Listen

Go to the Physics 30 Multimedia DVD and watch the video "The Millikan Experiment: Part 2" to see Millikan's experimental design and apparatus.

How did Millikan's Apparatus Work?

Go to the Physics 30 Multimedia DVD and open the "Millikan Experiment Simulation" to explore the experimental design.

The apparatus consists of a chamber (as shown below). Looking through the eyepiece, you would see something similar to that shown in the "Reticle View" mode. To switch to the reticle view, click the view button (🟢).

Apparatus View   Reticle View
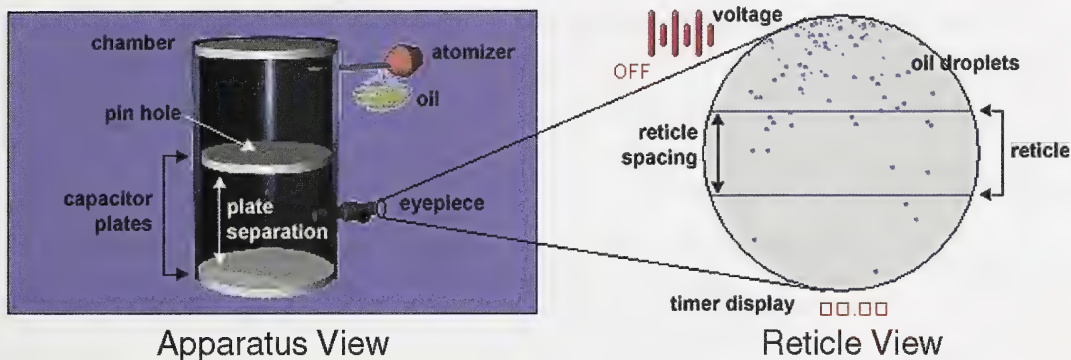
Go to the Physics 30 Multimedia DVD and open "Determining the Elementary Charge: Millikan's Oil Drop Experiment" to see how Millikan's oil drop experiment is used to determine the elementary charge.

Module 7: Lesson 2 Assignment

Go to the Module 7 Assignment Booklet and complete LAB 1.

Although time-consuming, Millikan's experiment was instrumental in establishing not only the value of the elementary charge, but also the quantized nature of electric charge. This follows Planck's earlier discovery that energy is also quantized.

Building on Thomson's work with the charge-to-mass ratio of an electron, it was then possible to determine the mass of an electron as 9.11×10^{-31} kg.

From J. J. Thomson:

$$\frac{q_e}{m_e} = 1.67 \times 10^{11} \text{ C/kg}$$

From R. A. Millikan:

$$q_e = e$$
$$= 1.60 \times 10^{-19} \text{ C}$$

Combined:

$$\frac{1.60 \times 10^{-19}\,C}{m_e} = 1.67 \times 10^{11}\,C/kg$$

$$m_e = 9.11 \times 10^{-31}\,kg$$

Due to rounding and significant digits, the value is extremely close to the accepted mass of the electron 9.11×10^{-31} kg.

By accelerating hydrogen ions (protons) through a potential difference and determining their charge-to-mass ratio, it was found that their mass was 1.67×10^{-27} kg. Together, Thomson and Millikan had essentially weighed and measured the charge of some of the smallest fundamental particles that make up matter. They also confirmed the idea that the atom was not the smallest form of matter and that it had divisible parts.

Analysis of Millikan's Experiment

+ + + +

$F_e = Eq$

oil drop

$F_g = mg$
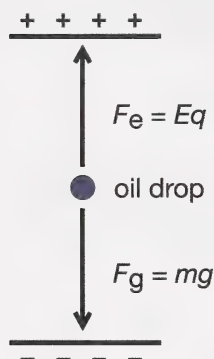
Millikan's original analysis can be simplified by assuming that the droplets can become suspended between the plates (eliminating any drag forces). That meant that the droplets experienced an electric force upward, exactly equal to the gravitational force pulling them down.

If a droplet were suspended, then the electrical force pulling it up would exactly balance the gravitational force pulling it down. Therefore,

$$\sum \vec{F} = 0 = \vec{F}_g + \vec{F}_e$$
$$\vec{F}_e = \vec{F}_g$$
$$\vec{E}q = mg$$
$$\left(\frac{V}{d}\right)q = mg$$
$$q = \frac{mgd}{V}$$

Note: F_g and F_e are opposite directions.

Read

Read "Millikan's Oil-drop Experiment" on pages 761 to 764 of the textbook.

Example Problem 1. An oil droplet with a mass of 9.80×10^{-16} kg is suspended between two horizontal charged plates. If the electric field strength between the plates is 2.0×10^4 V/m, what is the charge on the oil droplets?

Given

$m = 9.80 \times 10^{-16}$ kg

$\vec{E} = 2.0 \times 10^4$ V/m

Required

$$\vec{F}_E = \vec{F}_g$$
$$\vec{E}q = m\vec{g}$$
$$q = \frac{m\vec{g}}{\vec{E}}$$
$$q = \frac{\left(9.80 \times 10^{-16} \text{ kg}\right)\left(9.81 \text{ m/s}^2\right)}{\left(2.0 \times 10^4 \text{ V/m}\right)}$$

the charge on the oil drop $q = 4.8 \times 10^{-19}$ C

Analysis and Solution

Paraphrase

The charge on the drop is 4.8×10^{-19} C.

Example Problem 2. An oil droplet with a weight of 4.80×10^{-14} N is suspended between two horizontal charged plates that are 5.00 cm apart. If the potential difference between the plates is 3.0×10^3 V, how many excess electrons does the oil droplet carry?

Given

$\vec{F}_g = 4.80 \times 10^{-14}$ N

$d = 5.00$ cm

$\quad = 5.00 \times 10^{-2}$ m

$V = 3.0 \times 10^3$ V

Required

the number of excess electrons the oil drop carries

Analysis and Solution

$$\vec{F}_E = W$$
$$\vec{E}q = W$$
$$\frac{Vq}{d} = W$$
$$q = \frac{Wd}{V}$$
$$q = \frac{\left(4.80 \times 10^{-14}\ \text{N}\right)\left(5.00 \times 10^{-2}\ \text{m}\right)}{3.0 \times 10^3\ \text{V/m}}$$
$$q = 8.00 \times 10^{-19}\ \text{C}$$
$$\#e = \frac{8.00 \times 10^{-19}\ \text{C}}{1.60 \times 10^{-19}\ \text{C}}$$
$$\#e = 5e$$

Paraphrase

The oil drop has five excess electrons.

Self-Check

SC 1. An oil droplet weighs 3.84×10^{-15} N. If it is at rest between two horizontal plates with an electric field strength of 1.20×104 N/C, what is the charge on the oil droplet?

SC 2. An oil droplet with a mass of 4.80×10^{-16} kg is suspended between two horizontal charged plates that are 6.00 cm apart. If the potential difference between the plates is 588 V, how many excess electrons are on the droplet?

SC 3. Is it possible to have a particle with a charge of 2.00×10^{-19} C? Explain why or why not.

Check your work with the answers in the Appendix.

Try This

TR 1. A student does a Millikan oil drop experiment. The device has parallel plates that are 5.00 mm apart. The student determines that the mass of the drop is 2.90×10^{-15} kg. The student measures how the voltage affects the upward acceleration of the drop. The measurements are listed below.

Voltage (V)	Acceleration Upward (m/s²)
0	−9.81
100	−5.40
200	−0.98
300	3.43
400	7.85
500	12.26

    a. What are the manipulated and the responding variables?
    b. Draw a graph of the results.
    c. Use the graph to determine the voltage when the electric force and the force of gravity are balanced.
    d. Use your value from c. to determine the charge on the drop.
    e. How many excess electrons are on the drop?

TR 2. An oil droplet with a mass of 7.20×10^{-16} kg is moving upward at a constant speed of 2.00 m/s between two horizontal charged plates. If the electric field strength between the plates is 2.20×10^4 V/m, what is the charge on the oil droplet?

TR 3. An oil droplet with a mass of 3.50×10^{-15} kg accelerates downward at a rate of 2.50 m/s² when it is between two horizontal charged plates that are 1.00 cm apart. Assuming that the excess charge on the droplet is negative and the top plate is positive, how many excess electrons does the droplet carry if the potential difference between the plates is 533 V?

TR 4. An oil droplet with a mass of 5.70×10^{-16} kg accelerates upward at a rate of 2.90 m/s² when it is between two horizontal charged plates that are 3.50 cm apart.

    a. Draw a free-body diagram of the forces acting on the oil drop.
    b. If the potential difference between the plates is 792 V, what is the charge of the droplet?

Module 7: Lesson 2 Assignment

Go to the Module 7 Assignment Booklet and complete A 1, A 2, A 3, A 4, A 5 and D 1 (see below before responding to D 1).

▼ Discuss

Remember to record your response to D 1 in the Module 7 Assignment Booklet.

D 1. Millikan's experimental discoveries are, to some extent, a product of the scientific culture in which he lived and worked. Go to the Physics 30 Multimedia DVD and view the video clip, "Millikan—Scientific Climate." Summarize the scientific climate in which Millikan performed his work.

D 2. Millikan's published work is very different than that of his scientific journal. This has called into question the scientific process and highlights the use of scientific judgment. Go to the Physics 30 Multimedia DVD and view the video clip, "Millikan—Scientific Judgment" and describe how Millikan applied scientific judgment.

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Foundation 1923

◢ Lesson Summary

Millikan's experimental design was based on measuring the charge of many oil droplets and comparing them, reasoning that the smallest difference in charge among all the droplets would be due to the presence of one extra electron. That small difference in charge would then be equal to the charge of a single electron—the elementary unit of charge. Using the charge on numerous oil droplets and through careful analysis, Millikan discovered that the charges of the oil droplets were always integer multiples of 1.602×10^{-19} C. He reasoned this must be the charge of a single electron, a value that is referred to as the elementary charge.

The charge on each oil drop was determined by measuring, based on the motion of the droplet, the amount of electrical force that acts on it in a uniform electrical field. Oil droplets charged by friction were injected into a sealed vessel with electrodes on either end. Applying a voltage across the electrodes produced an electrical force that acted on the droplet, causing it to move upwards at a constant speed. Measuring the fall and rise speeds, Millikan determined the radius, volume, mass, and, ultimately, the charge of the droplet. By comparing many hundreds of droplets, the smallest integer difference in charge revealed the charge on one electron.

Although time-consuming, his experiment was instrumental in establishing not only the value of the elementary charge, but also the quantized nature of electric charge. It also confirmed the idea that the atom was not the smallest form of matter and that it had divisible parts.

Lesson Glossary

elementary unit of charge: the charge of an electron or a proton, 1.60×10^{-19} C

Lesson 3—The Rutherford and Bohr Models of the Atom

▽ Get Focused

This image shows the full visible spectrum of colours emitted by the surface of the Sun as observed at the McMath-Pierce Solar Observatory. Recall from Module 5 that when full-spectrum white light passes through a prism, it is dispersed into a spectrum as each wavelength refracts at a slightly different angle. Notice that there are some missing wavelengths, seen as black spots, and that the sunlight is composed mostly of yellow-green wavelengths.

At first glance, the dark spots in this spectrum seem random and unrelated to one another; but they are, in fact, strong evidence that the Sun's surface is composed of approximately 74% hydrogen and 25% helium. The relative
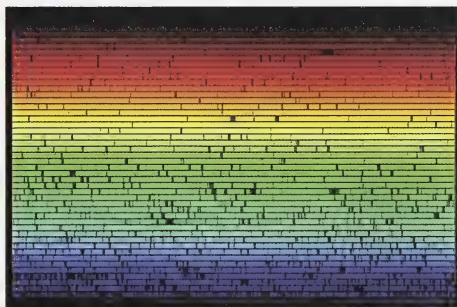
Image courtesy of the National Optical Astronomy Observatory/ Association of Universities for Research in Astronomy/National Science Foundation

amount and presence of these elements is related to the nuclear reactions that generate the Sun's energy. In a similar way to that of a mass spectrometer analyzing the composition of Titan's atmosphere, knowledge of the far and wide originated from an understanding of the close-up and invisibly small. As ideas of the atom evolved from Thomson's raisin-bun to Rutherford's planetary system and eventually to Bohr's concept of the stationary state, the colour of light emitted or absorbed by matter has taken on more significance, hinting at the very composition of the matter with which it interacts!

In Lesson 3 you will explore the fundamental makeup of matter that is revealed by its interaction with electromagnetic radiation and charged particles.

In this lesson you will answer the following essential questions:

- What does the Rutherford Scattering Experiment suggest about the nature of the nucleus, and how did it lead to the planetary model of the atom?

- What is the Bohr model of the atom, and how is the concept of stationary states and energy quantization used to explain how a gas absorbs and emits only certain wavelengths of electromagnetic radiation?

▽ Module 7: Lesson 3 Assignment

Your teacher-marked Module 7: Lesson 3 Assignment requires you to submit responses to the following:

- Lab—LAB 1 and LAB 2
- Assignment—A 1, A 2, A 3, A 4, A 5, A 6, A 7, and A8

The other questions in this lesson are not marked by the teacher; however, you should still answer these questions. The Self-Check and Try This questions are placed in this lesson to help you review important information and build key concepts that may be applied in future lessons.
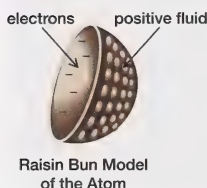
After a discussion with your teacher, you must decide what to do with the questions that are not part of your assignment. For example, you may decide to submit to your teacher the responses to Try This questions that are not marked. You should record the answers to all questions in this lesson and place those answers in your course folder.

Explore

electrons   positive fluid

Raisin Bun Model
of the Atom

When J. J. Thomson discovered the electron in 1897, it became evident that the atom was not the smallest unit of matter. Moreover, since electrons are negatively charged but atoms are neutral, atoms must also consist of a positively charged substance. Recall that Thomson's model described the atom as electrons embedded throughout a positively charged substance. Thomson's model is often called the raisin-bun model or the plum pudding model.

Planetary Model
of the Atom
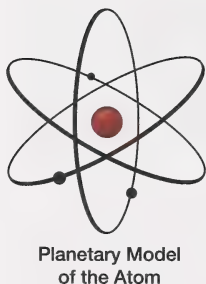
Thomson's model had a relatively short lifespan. As new investigations into the infinitely small continued and evidence was gathered, it became clear that within the atom there existed an extremely tiny, but very massive, positively charged core, giving rise to the planetary model of the atom. Evidence supporting this idea was collected by Ernest Rutherford and his assistants, Hans Geiger and Ernest Marsden, who observed the scattering of positively charged particles as they encountered a thin layer of gold atoms.

Go to the Physics 30 Multimedia DVD and view "Planetary Model of the Atom." (Note: When you follow the link, do not read the lesson the link brings you to. Instead, scroll down until you see the animated planetary model of the atom. Consider the animated model and then close the document)

In their experiment, positively charged helium ions (called alpha particles) from a small sample of radioactive radium were used to bombard gold atoms. When the charged alpha particles encountered gold atoms, they were scattered at various angles. The scattered alpha particles could be observed when they encountered a zinc sulfide screen attached to a microscope.
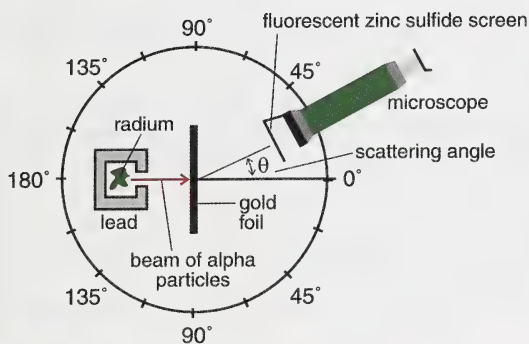
Read

Read "Rutherford's Scattering Experiment" on pages 767 and 768 of the textbook.

Watch and Listen

Go to the Physics 30 Multimedia DVD and open the "Rutherford Scattering Simulation" to see how a large nucleus scatters smaller, charged alpha particles. (Note that you will need to save this simulation to your desktop before using it.)

Notice in the simulation that alpha particles are composed of two red protons and two grey neutrons without any electrons, producing the characteristic +2 ion charge. Also notice the small but very distant electron that orbits the large nucleus.

You will see it pass along its circular path in the corners of the viewing area, giving a sense of how small the nucleus and electron are relative to the majority of empty space in the planetary model of the atom.
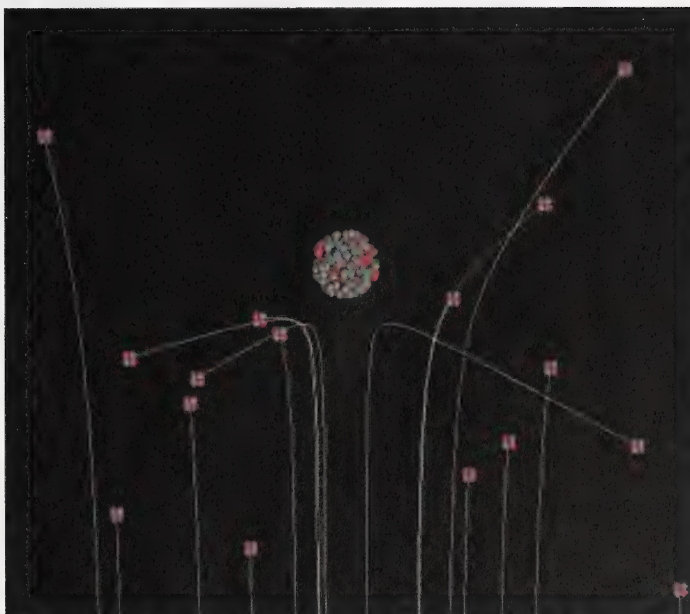
![Self-Check icon] **Self-Check**

SC 1. Adjust the number of protons on the atom using the simulation slider. Set it to 20 protons. Select "Show Traces" to see the path of each alpha particle. Use the term *many*, *few*, or *rare* to complete the following three statements:

a. _____ of the alpha particles pass by with little or no scattering, indicating the atom was mostly empty space.

b. _____ of the alpha particles are scattered at large angles, indicating the presence of a small, dense nucleus.

c. On occasion, _____ alpha particles are scattered straight back toward the source, indicating the presence of a very dense, positively charged nucleus. Presumably, a large electrostatic force of repulsion would be required to reverse the alpha particles' direction of motion.

Check your work with the answers in the Appendix.

Lab

![Question icon] **Module 7: Lesson 3 Assignment**

Go to the Module 7 Assignment Booklet and complete LAB 1 and LAB 2. You will need to go to the Physics 30 Multimedia DVD and open the "Rutherford Scattering Simulation" in order to respond to the questions.
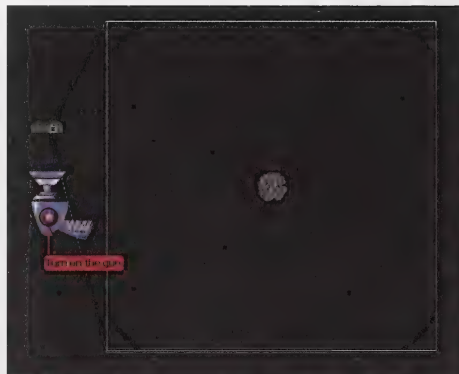
Failure of the Rutherford Model

According to Rutherford, the scattering alpha particles indicated that within the atom there existed a tiny, but very massive, positively charged core. Rutherford concluded that the atom was not filled with a positively charged substance (as Thomson had described); rather, all the positive charge of the atom was located in a nucleus at the centre of the atom. This nucleus was small but contained almost all the mass of the atom. Thus, Rutherford proposed a nuclear model. In this model the atom has a dense nucleus with relatively vast amounts of empty space through which the electrons can pass. The negative charge of the orbiting electrons was the opposite of the positive charge of the nucleus; so, overall, the atom is still electrically neutral, as Dalton determined.

Watch and Listen

Go to the Physics 30 Multimedia DVD and look at the animated "Planetary Model of the Atom" again. Remember, when you open the multimedia item, do not read the lesson to which the link takes you. Instead, scroll down until you see the animated planetary model of the atom. Consider the model and then close the multimedia piece.
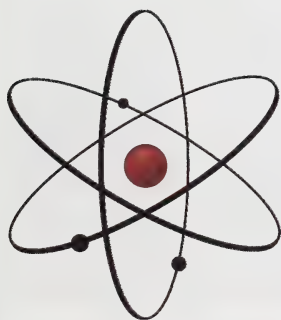
**Planetary Model
of the Atom**

There was a problem with the nuclear model of the atom. Recall that positive and negative charges attract. If the nucleus were positively charged, then what stopped the electrons from being sucked into the nucleus? To deal with this problem, Rutherford suggested that the electrons orbit the nucleus, much like the moon orbits Earth or like Earth orbits the sun. The force of attraction between the electrons and the nucleus provides the force necessary to keep the electrons in orbit. Hence, Rutherford proposed a planetary model of the atom.

However, the planetary model was also severely flawed. See if you can figure out what the flaw is by answering the following questions.

Try This

TR 1. According Maxwell's theory of electromagnetism, from Module 5: Lesson 1, what happens when an electron is accelerated? What is given off?

TR 2. In Rutherford's planetary model of the atom, are the electrons accelerated? If so, what force causes the acceleration?

TR 3. What would happen to an atom if electrons emitted radiation as they orbit the nucleus? Would atoms even exist if they constantly lost energy in the form of emitted radiation?

You should have discovered that, according to Rutherford's model, atoms are not stable and will collapse in on themselves. According to Maxwell's electromagnetic theory, when charged particles like electrons are accelerated, they emit electromagnetic radiation. Electrons orbiting a nucleus undergo inward acceleration; thus, they should continuously emit electromagnetic radiation. And if the electrons emit electromagnetic radiation, they should be losing energy. And if the electrons lose energy, they will eventually spiral into the nucleus. What was going on? By the end of the 19th century an adequate model of the atom had not yet surfaced.

◭ Read

Read "The Bohr Model of the Atom" on pages 771 of your physics textbook.

The Role of Atomic Spectra

In developing a model of the atom, scientists also had to contend with atomic spectra. By the early 1800s, scientists knew that every element emits unique line spectra. For example, when an evacuated bulb is filled with neon gas and a voltage is applied to the electrodes, a characteristic red glow is emitted.

Separating this light by wavelength reveals that neon gas is actually emitting a small collection of unique wavelengths that fall in the red to yellow region of the visible light spectrum. You can see these unique wavelengths identified on the line spectrum below the bulbs. If the bulb were filled with a different gas, for example argon, a blue colour would be produced, with a different and unique line spectrum. The line spectrum is like a chemical fingerprint with each element having its own distinct pattern.

Why did each element have unique spectra, and why was it a line spectra? Somehow, these phenomena must be tied into the mystery of atomic structure.

It is important to understand what a line spectrum means. There are three types of spectra: continuous, bright line (emission), and dark line (absorption). A glowing solid or liquid or high-pressure gas will produce a continuous spectrum but only low-pressure gases will produce line spectra.

Continuous Spectra

All wavelengths (and frequencies) of light are present. In the visible range (400 nm to 700 nm), all the colours are visible.
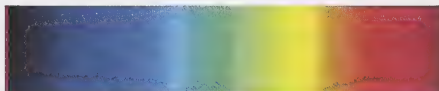
Continuous spectrum in the visible range.

Bright Line Spectra

An excited low-pressure gas produces a bright line spectrum. The spectrum only consists of lines of particular wavelength. A bright line spectrum is also called an **emission spectrum** because the gas emits certain wavelengths (frequencies).
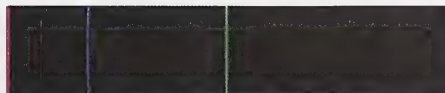
Emission spectrum for hydrogen in the visible range.

emission spectrum: a pattern of bright lines produced by a hot gas at low pressure

Here is a diagram of the experimental set-up to produce a bright line spectrum.
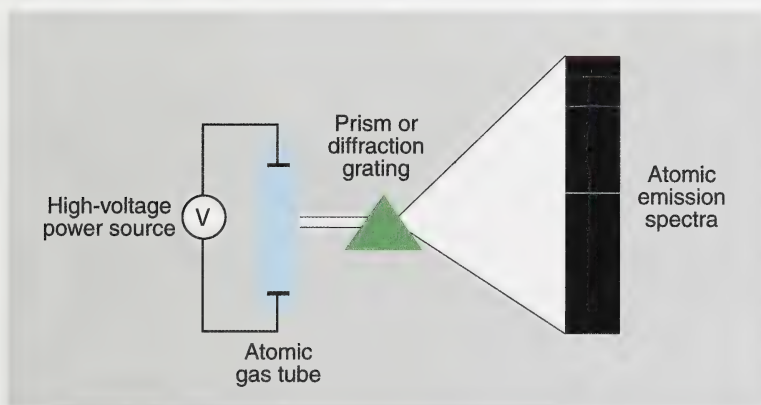
Dark Line Spectra

A dark line spectrum is created when light from a glowing solid or liquid is passed through an unexcited (cool) gas. The typically continuous spectrum (from the glowing solid or liquid) is now missing certain wavelengths—these missing wavelengths appear as dark lines. A dark line spectrum is called an **absorption spectrum** because the gas absorbs certain wavelengths (frequencies).
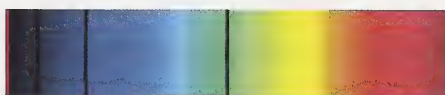
Absorption spectrum for hydrogen in the visible range.

absorption spectrum: a pattern of dark lines produced when light passes through a gas at low pressure
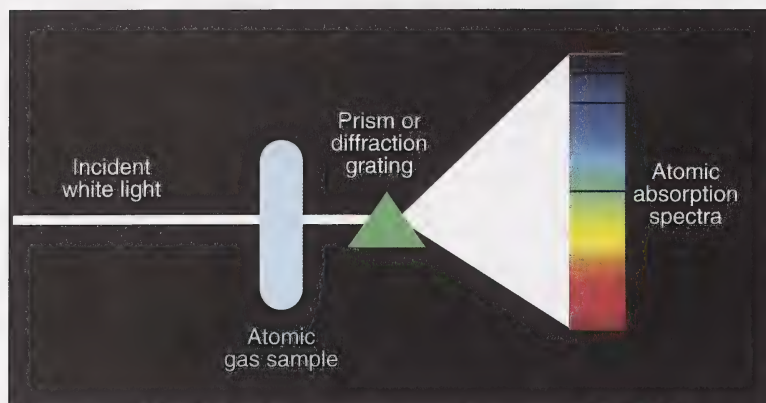
Self-Check

SC 2. The emission and absorption spectra of hydrogen are displayed above. Compare the position of these lines. What do you notice? Does this mean that a gas can only absorb and emit a limited number of unique EMR wavelengths?

Check your work with the answer in the Appendix.

Try This

It is interesting to re-evaluate Rutherford's planetary model of the atom in light of atomic spectra. Remember that Rutherford's model violated Maxwell's laws of electromagnetism. Ignore that flaw for the moment and evaluate Rutherford's model by investigating what it predicts about atomic spectra.

Module 7: Lesson 3 Assignment

Go to the Module 7 Assignment Booklet and answer A 1.

Read

Read "**Spectroscopy**"on pages 771 to 773 of your physics textbook.

spectroscopy: the study of the light emitted and absorbed by different materials

The Bohr Model of the Hydrogen Atom

At the beginning of the 20th century a model was proposed that finally began to answer some of the questions of atomic structure and spectra. In 1913 Niels Bohr proposed a model of atomic structure using hydrogen as the example model. Bohr's model not only described the structure of the atom, but it also explained atomic spectra and, furthermore, correctly predicted the existence of more atomic lines. Bohr's model seemed to be everything that physicists were looking for. But there was one problem—Bohr's model stepped outside the realm of classical physics and ventured into the newly emerging world of quantum physics. This left many scientists skeptical of the model. Nonetheless, Bohr's model was far superior to any previous model and was accepted as a semi-classical model of the atom.

Bohr's Postulates

Bohr started with a planetary model of the atom. However, to sidestep the problems that confounded Rutherford, Bohr made several assumptions, including the following:

stationary state: a stable state with a fixed energy level

energy level: a discrete and quantized amount of energy

- Electrons orbit the nucleus. They are held in orbit by an electrostatic force.

- Electrons can only be in certain, permitted orbits and an electron does not emit radiation when it is in one of these orbits. In these allowed orbits, the energy of the electron is constant. These orbits are called **stationary states**, since the electron's energy is constant. In other words, the energy of the electron is quantized—it can only have certain values (recall the concept of the "particle-in-a-box" from Module 6: Lesson 3 or page 734 in your textbook). Therefore, the allowed orbits can be referred to as energy states.

- An electron only emits radiation when it "falls" from a higher energy state to a lower state. The change in energy of the electron (from the higher state to the lower state) is equal to the energy of the emitted photon, thereby obeying the conservation of energy principle. Similarly, an electron only absorbs radiation when it "jumps" to a higher **energy level**. Again, the change in energy of the electron is now equal to the energy of the absorbed photon.

- The radii of the allowed orbits are also quantized since each energy state has a specific radius.

Bohr's model was allowed to have stationary states because of de Broglie's work on the wavelength of matter. The electron must have a certain speed in order for the F_{inward} and $F_{electric}$ to be equal. In order for this to occur, the electron has a specific wavelength, which happens to be equal to the circumference of the stationary state. The circumference of the second stationary state is equal to twice the electron's wavelength and so on. This agrees with quantum theory. See "Figure 15.24" on page 782 of the textbook.

By applying his assumptions, Bohr was able to develop expressions for the allowed energy levels and the allowed radii for the hydrogen atom. Using these expressions, Bohr calculated all the allowed electron energy levels for hydrogen.

Energy Level Diagram for Hydrogen

$E = 0$ $n = \infty$
$E = 0 - 0.85$ —— $n = 4$
$E = 0 - 1.51$ —— $n = 3$

$E = 0 - 3.40$ —— $n = 2$

Energy (eV)

$E = 0 - 13.6$ —— $n = 1$
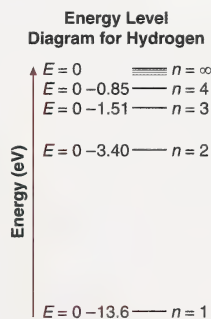
An energy level diagram, like the one shown here, often illustrates energy levels. An energy level diagram displays several things, such as:

- The energy levels of hydrogen are not evenly spaced. As an electron moves to higher and higher levels, the difference in energy between the levels becomes smaller and smaller.

- The energy of each level is reported as a negative number. As an electron moves to a higher energy level, its energy increases (becomes less negative).

- When an electron makes a transition, it moves from one energy level to another. The spacing between energy levels represents the magnitude of the change in energy of the electron. For example, an electron moving from $n = 3$ to $n = 1$ has a greater change in energy than an electron moving from $n = 3$ to $n = 2$

Watch and Listen

Go to the Physics 30 Multimedia DVD and view "Energy Levels of Hydrogen."

Bohr's model of the hydrogen atom successfully explained emission and absorption spectra. Not only did Bohr's model provide a conceptual description of emission and absorption spectra, it also correctly predicted the wavelength of the spectral lines in hydrogen's emission and absorption spectra. Furthermore, Bohr's model explained why absorption lines match emission lines.

According to Bohr's model, an electron only emits or absorbs energy when it moves between energy levels. The energy that is emitted or absorbed by an atom is in the form of a photon.

The amount of energy that is emitted or absorbed is the energy difference between the energy levels.	The frequency or wavelength of a photon is related to its energy.

The frequency or wavelength of a photon is related to its energy.

Expressed as an equation:

$$E = hf = \frac{hc}{\lambda}$$

Expressed as an equation:

$$\Delta E = E_f - E_i$$

Quantity	Symbol	SI Unit
change in energy	ΔE	J or eV
initial energy	E_i	J or eV
final energy	E_f	J or eV

Quantity	Symbol	SI Unit
photon energy	E	J or eV
Planck's constant	h	6.63×10^{-34} J•s or 4.14×10^{-15} eV•s
frequency	f	Hz
wavelength	λ	m
speed of light	c	3.00×10^8 m/s

Example Problem 1. A photon is absorbed by a hydrogen atom, causing an electron to jump from the $n = 1$ energy level to the $n = 3$ energy level. Using Hydrogen's energy level diagram, determine the change in energy of the electron and the wavelength of the absorbed photon.

Given

$n_i = 1$
$n_i = 3$
$E_1 = 13.6$ eV
$E_3 = 1.51$ eV

Required

the energy of the released photon and the wavelength of the photon

Energy Level Diagram for Hydrogen

$E = 0$ $n = \infty$
$E = 0 - 0.85$ —— $n = 4$
$E = 0 - 1.51$ —— $n = 3$

$E = 0 - 3.40$ —— $n = 2$

Energy (eV)

$E = 0 - 13.6$ —— $n = 1$

Analysis and Solution

The red arrow shows that an electron has made a transition from the $n = 1$ to the $n = 3$ energy level. The change in the electron's energy that occurs as a result of the transition is as follows:

$$\Delta E = E_f - E_i$$
$$\Delta E = (-1.51 \text{ eV}) - (-13.6 \text{ eV})$$
$$\Delta E = 12.09 \text{ eV}$$
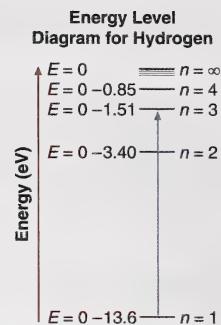
The change in the electron's energy is equal to the photon's energy, which is related to its wavelength as follows:

$$E = \frac{hc}{\lambda}$$
$$\lambda = \frac{hc}{E}$$
$$\lambda = \frac{\left(4.14 \times 10^{-15} \text{ eV} \cdot \text{s}\right)\left(3.00 \times 10^8 \text{ m/s}\right)}{12.09 \text{ eV}}$$
$$\lambda = 1.03 \times 10^{-7} \text{m}$$

Paraphrase

The energy of the photon is 12.09 eV and it has a wavelength of 1.03×10^{-7} m.

Watch and Listen

To simulate the example problem transition and see the dark line spectrum that results, go to the Physics 30 Multimedia DVD and open the "Hydrogen Atom Simulation." On the simulation, press "play" and select the

(■ ■ ■) probability cloud representation. Next, select the $n = 3$ transition.
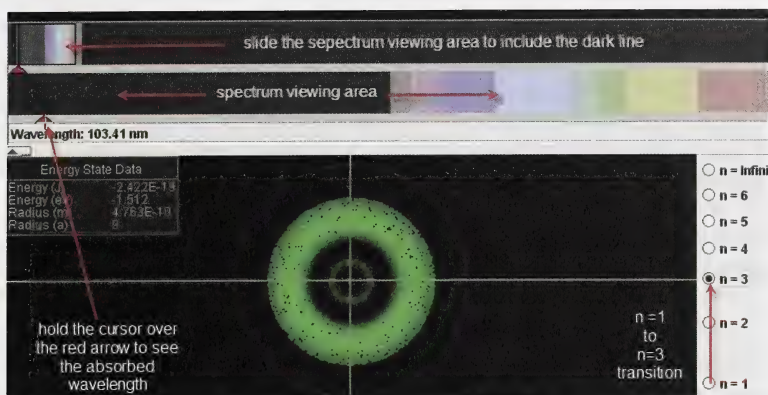
Using this simulation, see if you can verify each of the points below, summarizing the Bohr Model of the atom.

Summary of the Bohr Model

- **Absorption ($n_f > n_i$).** When an electron "jumps" to a higher energy level, it must absorb energy. Each transition requires a specific amount of energy. The dark lines in an absorption spectrum correspond to specific photon wavelengths that are needed for an electron to jump from lower to higher energy levels.

> **absorption spectrum:** a pattern of dark lines produced when light passes through a gas at low pressure.
>
> **emission spectrum:** a pattern of bright lines produced by a hot gas at low pressure

- **Emission ($n_f < n_i$).** When an electron "falls" to a lower energy level, energy is emitted. Each transition emits a specific amount of energy. The lines that are seen in an emission spectrum correspond to specific photon wavelengths that are emitted when an electron jumps from higher to lower energy levels.

- Absorption and emission lines match. For example, the magnitude of the change in energy (ΔE) when an electron rises from $n = 1$ to $n = 2$ is equal to the magnitude of the change in energy (ΔE) when an electron falls from $n = 2$ to $n = 1$.

- The absolute value, or the magnitude of the change in energy, is calculated based on the initial and final energy of the electron that undergoes a transition:

$$\Delta E = E_f - E_i$$

- The frequency or wavelength of an absorbed or emitted photon can be calculated with $E = hf = \dfrac{hc}{\lambda}$.

Read

Read "The Bohr Model of the Atom" on pages 773 to 780 of your physics textbook.

Self-Check

Test your understanding of Bohr's model of the hydrogen atom by answering the following questions. For questions involving calculations, you may use the "Hydrogen Atom Simulation," available on the Physics 30 Multimedia DVD, to verify your answers.

SC 3. Look at the assumptions Bohr made. Which of these assumptions "fit" with classical physics and which support the ideas of quantum physics?

SC 4. Sample equipment to show atomic absorption lines is shown in the diagram below. Absorption lines occur in atomic spectra when an electron absorbs the energy. The electron quickly drops back to the ground state, releasing a photon with the same amount of energy that was absorbed. If the photon is released, why does it not show up on the atomic spectra?
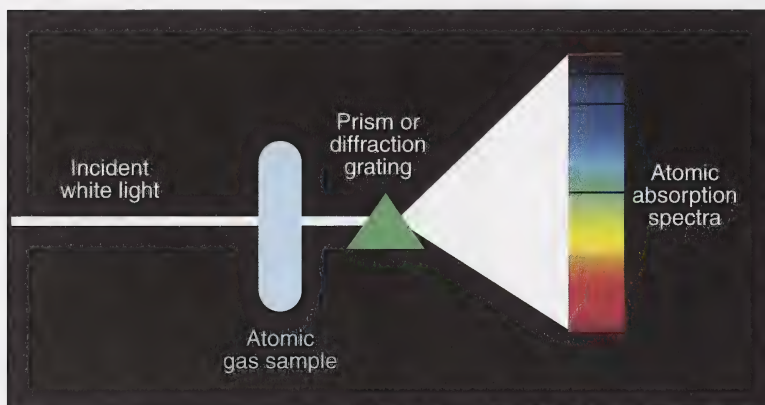
Check your work with the answers in the Appendix.

Continue to test your understanding of Bohr's model of the hydrogen atom by answering the following questions. As in the Self-Check activity above, for questions involving calculations, you may use the "Hydrogen Atom Simulation," available on the Physics 30 Multimedia DVD, to verify your answers.

Module 7: Lesson 3 Assignment

Go to the Module 7 Assignment Booklet and complete A 2, A 3, A 4, A 5, A 6, A 7, and A 8.

Try This

Go to the Physics 30 Multimedia DVD to retrieve the two simulations used in these Try This questions.

TR 4. Use the "Bohr Model of Hydrogen Simulation" to shoot a stream of photons through a container of hydrogen gas. Observe how photons of certain energies are absorbed, causing changes in the orbits of electrons. Build the spectrum of hydrogen based on photons that are absorbed and emitted.

TR 5. You can also use the "Bohr Model: Introduction Simulation" to fire photons and observe how an absorbed photon changes the orbit of an electron, and how a photon is emitted from an excited electron. Calculate the energies of absorbed and emitted photons based on energy level diagrams. The light energy produced by the laser can be modulated, and a lamp can be used to view the entire absorption spectrum at once.

Reflect and Connect

The Bohr model of the atom, in conjunction with spectroscopy, can be used to identify unknown gases based on either their absorption or emission line spectrums. The missing parts of the sun's spectrum can be explained using the absorption spectrum of hydrogen and helium, indicating their presence on the surface of the sun.

Using a similar technique, it is possible to identify the chemical composition of other stars and galaxies by examining the wavelengths of light that come from them.

RC 1. Go to the Physics 30 Multimedia DVD and open the "Star Spectra Simulation." See if you can identify the presence of known elements using the line spectrum from astronomical objects such as stars and galaxies.

Going Beyond—The Quantum Mechanical Model of the Hydrogen Atom

With the development of quantum mechanics throughout the 20th century, a quantum mechanical model of the atom has been devised. Bohr's model of the hydrogen atom was a semi-classical model—it took ideas from classical physics and extended them to quantum physics. A quantum mechanical model of the hydrogen atom does not rely on classical physics; rather, it is built upon ideas of wave functions and probabilities.

In the quantum model of the atom, electrons do not exist in specific orbits around a nucleus. Rather, the quantum model computes probabilities for the location of an electron around a nucleus. Remember that Bohr's model stated that an electron can only exist in specific orbits, with a specific energy and radius. The quantum model denies these absolute ideas. An electron can exist anywhere around a nucleus—the probability distribution represents the most likely location of the electron.

The "Hydrogen Atom Simulation," available on the Physics 30 Multimedia DVD, can be used to compare the quantum model of the hydrogen atom to Bohr's model of the hydrogen atom. On the simulation, the allowed Bohr radii are drawn as circles. Remember that the scintillations (flashes of light) represent probabilities—the brighter the flash, the greater the probability.

Self-Check

SC 5. Play the Hydrogen Atom Simulation and select the probability cloud mode ( ). Make sure that the electron is in its ground state ($n = 1$). Vary the scintillation rate using the slider.

a. The diagram below shows the first three allowed Bohr radii for hydrogen. On a diagram like the one shown, sketch the probability density for an electron in the ground state ($n = 1$), according to the quantum mechanical model of hydrogen. Indicate the region(s) of highest probability on your diagram.
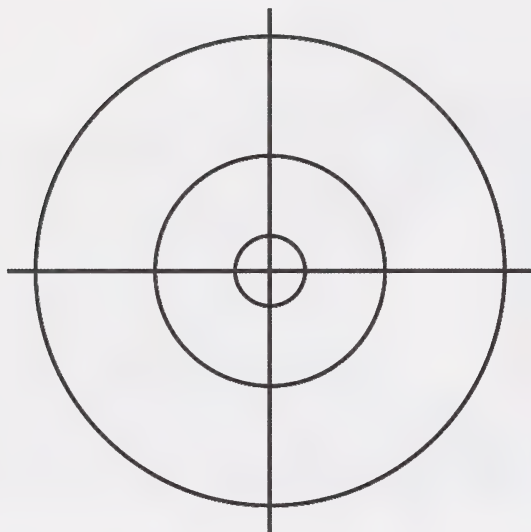
b. How does the quantum mechanical model for the ground state of hydrogen compare to the Bohr model for the ground state?

SC 6. Reset the simulation so that the electron is in the ground state ($n = 1$). Do a transition to the second energy level. Again, vary the scintillation rate and toggle between modes.

a. Sketch the probability density for an electron in the second energy level. Indicate the region(s) of highest probability on your diagram.
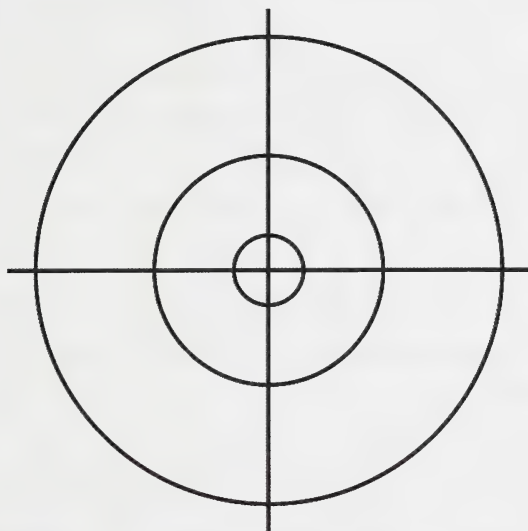
b. How does the quantum mechanical model for an electron in the second energy level of hydrogen compare to the Bohr model for the ground state?

Check your work with the answers in the Appendix.

Lesson Summary

In this lesson you explored the following questions:

- What does the Rutherford Scattering Experiment suggest about the nature of the nucleus, and how did it lead to the planetary model of the atom?

- What is the Bohr model of the atom, and how is the concept of stationary states and energy quantization used to explain how a gas absorbs and emits only certain wavelengths of electromagnetic radiation?

Rutherford's Scattering Experiment was significant because he expected to verify the J. J. Thomson model of the atom and have the alpha particles travel straight through the gold foil. Instead, he was surprised to discover that some of the alpha particles were significantly deflected by something in the atom. His observations led him to develop a new model of the atom with a small, dense centre with most of the mass and a positive charge that was named the nucleus. In order to balance the charge, the electrons orbited around the nucleus like planets orbiting around the sun. He maintained the net neutral electrical charge and the electrons as discovered by Thomson, but the discovery of the nucleus was a new advance.

Bohr quickly realized that the Rutherford model with the orbiting electrons was flawed. In order for electrons to orbit (move in a circle), they must constantly accelerate. According the Maxwell's electromagnetic theory, this means that the electrons would constantly be emitting EMR and losing energy. As a result, the electrons would slow down and spiral into the nucleus. Clearly, this wasn't happening, so changes to the model were needed. Bohr used spectroscopy to examine the patterns of specific wavelengths of EMR absorbed and emitted by gaseous elements. From these observations he determined that the electrons were in specific orbitals and could only gain and release specific amounts of energy—quantized energy. Bohr established that electrons in the atom have quantized orbitals and that the electrons absorb specific energy photons to go up orbital levels and release specific energy photons when they drop down orbital levels. However, Bohr could not explain why there were orbital levels at those specific energies. Bohr's model is considered semi-classical because it incorporates the quantum but does not include the wave-duality of the electron, which was discovered later.

The quantum mechanical model links the Bohr model with de Broglie wavelengths for electrons. The stationary orbitals are stable because the circumference of the orbital is a whole number multiple of the wavelength of the electron. If the orbital circumference is not a whole number multiple, then the electron destructively interferes with itself and the orbital is not stable. Due to Heisenberg's uncertainty principle, it is impossible to predict exactly where the electrons are located, but the probability cloud of where the electron is can be calculated. Quantum theory cannot predict exactly where the electron is, but it allows physicist to calculate the probability of it being in a specific location. Future physics courses will show you that physics has changed from classical physics with exact answers to quantum physics with probabilities of answers.

Theories about the composition and structure of the atom are constantly changing, and it is important to remember that scientific models are human inventions. They are tools developed to help explain physical phenomena. As such, models are not a literal representation of the world. Rather, they illustrate a way of looking at the world and a way of understanding certain phenomena. As science continues to uncover secrets of the atom, new models will evolve.

Lesson Glossary

absorption spectrum: a pattern of dark lines produced when light passes through a gas at low pressure

emission spectrum: a pattern of bright lines produced by a hot gas at low pressure

energy level: a discrete and quantized amount of energy

spectroscopy: the study of the light emitted and absorbed by different materials

stationary state: a stable state with a fixed energy level

Module 7—Investigating the Nature of the Atom

◢ Module Summary

Module 7 focused on how the quantization of energy in atoms and nuclei reveal the electrical nature of the atom. Early work with vacuum tubes and electric potential led to the discovery of the cathode ray, which served as a vehicle for investigations into the nature of the particles that produced it. Experimentation and observations of cathode rays indicated that they were negatively charged particles capable of being deflected by magnetic and electric fields and possessing the particle characteristics of kinetic energy and momentum.

Using the cathode ray, J. J. Thomson determined the charge-to-mass ratio of these particles by first measuring their speed with perpendicular electric and magnetic fields and then by using only a magnetic field to produce uniform circular motion. Thomson concluded that the unique charge-to-mass ratio for all cathode ray particles is 1.76×10^{11} C/kg, a ratio thousands of times larger than that of any other common particle, such as the hydrogen ion. The large ratio could indicate a relatively large charge and/or relatively small mass. In this case it was the small mass that led to a large q/m (charge-to-mass) ratio.

The concepts and theories used in Thomson's original experiment are now commonly applied in mass spectrometer technology. This technology can be used to identify unknown chemicals by comparing the unique charge-to-mass ratio of the unknown compound to that of the charge-to-mass ratio of other known compounds.

Millikan discovered the elementary charge of an electron in his now-famous oil drop experiment. By finding the smallest difference in charge between thousands of oil drops, he was able to conclude that the electron has a charge of -1.602×10^{-19} C—a value that is now referred to as the elementary charge. Although time-consuming, his experiment was instrumental in establishing not only the value of the elementary charge, but also the quantized nature of electric charge—an oil drop's charge can only be an integer multiple of the elementary charge. It also confirmed the idea that the atom was not the smallest form of matter and that it is divisible into subatomic particles.

After the electron had been identified and studied, the nature of the nucleus was revealed by Rutherford's scattering experiment, leading to the planetary model of the atom. This model was difficult in terms of classical physics and required significant revisions, which were done courtesy of Niels Bohr. Bohr's Semi-Classical Model described electrons orbiting the nucleus in certain stable states (energy levels) with specific energies and radii. This quantization of the energy explained patterns in the EMR spectrum of certain elements, leading to the identification of atoms and elements on distant objects such as the sun.

Finally, the quantum mechanical model of the atom described the electron position using a probability distribution, a distribution that indicates where the electron is most likely to be found.

Theories about the composition and structure of the atom are constantly changing, and it is important to remember that scientific models are human inventions. They are tools developed to help explain physical phenomena. As such, models are not a literal representation of the world. Rather, they illustrate a way of looking at the world and a way of understanding certain phenomena. As science continues to uncover secrets of the atom, new models will evolve. Hence, an artistic representation of electrons orbiting a nucleus is just that—a representation of something that cannot be seen by the human eye but can be understood by the human brain.

⚠️ Module Assessment

Use the information below to answer the following questions.

Question 1

In a modified Millikan apparatus, a small charged object with a mass of 4.7×10^{-15} kg is suspended by the electric field that is between charged parallel plates. The table below shows how the balancing voltage depends on the distance between the plates.

Plate Separation (mm)	Balancing Voltage (x 10^3 V)
10.2	0.992
21.0	1.99
25.1	2.44
29.0	2.85
35.0	3.52
55.0	

- Graph the balancing voltage as a function of the plate separation with the manipulated variable on the horizontal axis.

_____ (title)

_____

_____

_____
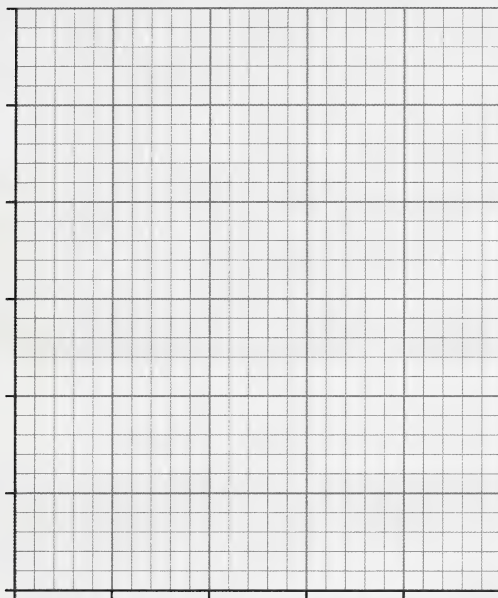
- Calculate the slope of the graph and describe the physical quantity or quantities that this slope represents.

- Using the slope, or another suitable averaging technique, determine the magnitude of the charge on the suspended mass.

- Determine the balancing voltage required when the plates are separated by 55.0 mm.

Clearly communicate your understanding of the physics principles that you are using to solve this question. You may communicate this understanding mathematically, graphically, and/or with written statements.

Go to the appendix to see the "Graphing Question Scoring Guide."

Question 2

Describe the development of the quantum mechanical model of the atom. In your explanation, start with the Dalton model of the atom and finish with the quantum mechanical model of the atom. For each of the five models include

- a description of the significant experiments
- the reason the observations of the experiment showed a new model was needed
- a description of how scientists changed each model into the next model

Go to the appendix to see the "Holistic Question Scoring Guide."

Module 7—Investigating the Nature of the Atom

Module Glossary

absorption spectrum: a pattern of dark lines produced when light passes through a gas at low pressure

cathode ray: a free electron emitted by a negative electrode in a low-pressure environment

elementary unit of charge: the charge of an electron or a proton, $1.60 \times 10{-}19$ C

emission spectrum: a pattern of bright lines produced by a hot gas at low pressure

energy level: a discrete and quantized amount of energy

spectroscopy: the study of the light emitted and absorbed by different materials

stationary state: a stable state with a fixed energy level

Graphing Question Scoring Guide

(5 marks)

Check the following before you submit your work:

- Did you put a title on the graph?
- Did you label each axis with an appropriate title including units?
- Are the axis scales appropriate to the size of the graph?
- Is the equation shown?
- Did you calculate the area and paraphrase the answer with the correct significant digits and appropriate units?

Scoring Guides for Graphing Skill-Based Questions—Mathematical Treatment

Score	Description
5	- All formulas are present. - All substitutions are given and are consistent with the graphed data. - The relationship between the slope, area, or intercept, and the appropriate physics is explicitly communicated. - The final answer is stated with appropriate significant digits and with appropriate units. Unit analysis is explicitly provided, if required. **Note:** one minor error may be present.*
4	- The response contains implicit treatment.** **or** - The response contains explicit treatment with up to three minor errors or one major error.***
3	- The response is incomplete but contains some valid progress toward answering the question; i.e., coordinates of relevant points are read correctly, including powers of 10 and units, and a valid substitution is shown.
2	- The coordinates of one relevant point are read. - The reason for requiring a point is addressed or implied.
1	- A valid start is present.
0	- Nothing appropriate to the mathematical treatment required is present.

*Minor errors include:

- Misreading a data value while interpolating or extrapolating up to one-half grid off.
- Stating the final answer with incorrect (but not disrespectful) units.
- Stating the final answer with incorrect (but not disrespectful) significant digits.
- Missing one of several different formulas.

**Implicit treatment means:

- Substituting appropriate values into a formula from the data sheets without stating the formula.
- Starting with memorized, derived formulas not given on the equations sheet.
- Substituting the value from one calculation into a second formula without communicating that the physics quantity in the two formulas is the same.

***Major errors include:

- Using off-line points (most often, this is calculating the slope using data points that are not on a linear line of best fit).
- Using a single data point ratio as the slope.
- Missing powers of 10 in interpolating or extrapolating.

Holistic Question Scoring Guide

(5 marks)

Check the following before you submit your work:

- Did you write your answer as a paragraph with proper sentences?
- Did you clearly answer all parts of the question?
- Did you state and explain any relevant physics principles as shown on your physics data sheet?
- Did you state and explain any relevant equations?

Holistic Scoring Guide

Score	Description
5	The nature of a response that will receive a score of 5 has the following characteristics: - The response addresses, with appropriate knowledge, all the major concepts in the question (all bullets must be attempted). - The student applies major physics principles in the response (appropriate physics principles are stated). - The relationships between ideas contained in the response are explicit* (physics principles are clearly linked to the application). - The reader has no difficulty following the strategy or solution presented by the student. - Statements made in the response are supported explicitly.* **Note:** the response may contain minor errors or have minor omissions.

4	The nature of a response that will receive a score of 4 has the following characteristics: • The response addresses, with appropriate knowledge, all the major concepts in the question (all bullets must be attempted). • The student applies major physics principles in the response (appropriate physics principles are stated). • The relationships between the ideas contained in the response are implied**(physics principles are stated but not properly linked to the application). • The reader has some difficulty following the strategy or solution presented by the student. • Statements made in the response are supported implicitly.** **Note:** the response is mostly complete and mostly correct, although it may contain errors or have omissions, and contains some application of physics principles.
3	The nature of a response that will receive a score of 3 has the following characteristics: • The response addresses, with some appropriate knowledge, all the major concepts in the question (all bullets must be attempted). • The student does not apply major physics principles in the response (all appropriate physics principles are not stated). • There are no relationships between the ideas contained in the response (physics principles are stated but not applied). • The reader may have difficulty following the strategy or solution presented by the student.
2	The nature of a response that will receive a score of 2 has the following characteristic: • The response addresses, with some appropriate knowledge, two of the major concepts in the question (only two bullets are attempted).
1	The nature of a response that will receive a score of 1 has the following characteristic: • The response addresses, with some appropriate knowledge, one of the major concepts in the question (only one bullet is attempted).
0	• The student provides a solution that is invalid for the question.

*Explicit means the response is clearly stated; the marker does not have to interpret.

**Implicit (implied) means the response is not clearly stated; the marker must interpret.

For example:

Explicit: An electron has a negative charge while a proton has a positive charge.

The answer is clear with no possible misinterpretation.

Implicit: An electron has a negative charge while a proton does not.

The answer is not clear because the marker does not know if a proton is neutral or positively charged. There is more than one possible way to interpret the answer.

Self-Check Answers

Contact your teacher if your answers vary significantly from the answers provided here.

Lesson 1

SC 1.

a. The direction of the electric field is the direction in which a positive particle is pushed; therefore, in a downward field, the negatively charged electron will go the opposite direction, upward.

b. Using the left hand rule for negatively charged particles in magnetic fields, the current is travelling to the right (thumb), the magnetic field is into the page (fingers) and the force on the particle is upward (palm faces up).

c. Since the electrons are undeflected, the forces—electrical force downward and magnetic force upward—are the same magnitude. The force of gravity is insignificant on such a small particle compared to the other forces, so it is ignored.
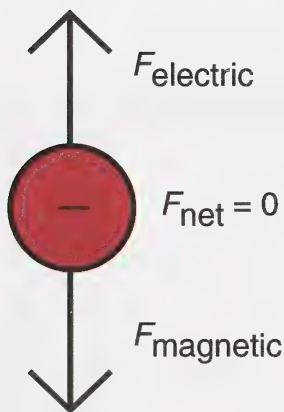
SC 2.

Given

$$\vec{E} = 100 \text{ v/m}$$
$$\vec{B} = 2.0 \text{ T}$$

Required

the velocity of the undeflected particle

$$v_\perp = \frac{\left|\vec{E}\right|}{\left|\vec{B}\right|}$$

$$v_\perp = \frac{(100 \text{ v/m})}{(2.0 \text{ T})}$$

$$v_\perp = 50.0 \text{ m/s}$$

Analysis and Solution

Paraphrase

The velocity of the particle is 50 m/s.

SC 3.

a. Proton

$$\frac{q}{m} = \frac{1.60 \times 10^{-19} \text{ C}}{1.67 \times 10^{-27} \text{ kg}}$$

$$= 9.58 \times 10^7 \text{ C/kg}$$

The charge-to-mass ratio of the proton is 9.58×10^7 C/kg.

b. Alpha particle

$$\frac{q}{m} = \frac{3.20 \times 10^{-19} \text{ C}}{6.65 \times 10^{-27} \text{ kg}}$$

$$= 4.81 \times 10^7 \text{ C/kg}$$

The charge-to-mass ratio of the alpha particle is 4.81×10^7 C/kg.

c. Neutron

$$\frac{q}{m} = \frac{0 \text{ C}}{1.67 \times 10^{-27} \text{ kg}}$$

$$= 0 \text{ C/kg}$$

The neutron is neutral, so it has no charge; as a result, the charge-to-mass ratio is zero.

SC 4.

Given

$\frac{q}{m}$ electron $= 1.76 \times 10^{11}$ C/kg

$\frac{q}{m}$ proton $= 9.58 \times 10^{7}$ C/kg

Required

the number of times larger the electron's charge-to-mass ratio is than the proton's charge-to-mass ratio

Analysis and Solution

$$\frac{\frac{q}{m} \text{ electron}}{\frac{q}{m} \text{ proton}} = \frac{1.76 \times 10^{11} \text{ C/kg}}{9.58 \times 10^{7} \text{ C/kg}}$$

$$= 1.84 \times 10^{3} \text{ times larger}$$

Paraphrase

The charge-to-mass ratio of the electron is 1.84×10^{3} larger.

SC 5.

Step 1: Determine the velocity of the electrons by measuring the **electric** and **magnetic** fields and using this equation:

$$v = \frac{|E|}{B}$$

Step 2: Turn off the **electric** field, leaving only the **magnetic** field, which acts perpendicularly to the velocity of the charged particle. In this orientation the magnetic force causes the charged particle to exhibit **uniform circular** motion, giving the following expression for the charge-to-mass ratio:

$$F_{\text{inward}} = F_{\text{m}}$$
$$\frac{mv^{2}}{r} = qvB$$
$$\frac{q}{m} = \frac{v}{Br}$$

SC 6. J. J. Thomson was able to generate cathode rays (electrons) from cathodes made of different elements. This showed that the cathode rays (electrons) came from within many different elements and must be part of the atom that had previously been undiscovered.

SC 7. J. J. Thomson started with neutral atoms (no net charge), which agreed with Dalton's model. However, the cathode rays coming from the cathode proved to be negatively charged. In order for the atom to be neutral the remaining part of the atom, once the electrons were removed, must be positively charged. The charges of the positive "bun" and negative "raisins" cancelled each other out and resulted in the neutral atom.

Lesson 2

SC 1.

Given

$$\vec{F}_g = 3.84 \times 10^{-15} \text{ N}$$
$$\vec{E} = 1.20 \times 10^4 \text{ N/C}$$

Required

the charge on the particle

Analysis and Solution

$$\vec{F}_e = \vec{F}_g$$
$$\vec{E}q = \vec{F}_g$$
$$q = \frac{\vec{F}_g}{E}$$
$$= \frac{\left(3.84 \times 10^{-15} \text{ N}\right)}{\left(1.20 \times 10^4 \text{ N/C}\right)}$$
$$= 3.20 \times 10^{-19} \text{ C}$$

Paraphrase

The charge on the particle is 3.20×10^{-19} C.

SC 2.

$$m = 4.80 \times 10^{-16} \text{ kg}$$
$$d = 6.00 \text{ cm} = 6.00 \times 10^{-2} \text{ m}$$
$$V = 588 \text{ V}$$

Required

the quantity of excess electrons on the particle

Analysis and Solution

Start with the two equal forces.

$$\vec{F}_e = \vec{F}_g$$

$$\vec{E}q = m\vec{g}$$

$$\left(\frac{V}{d}\right)q = mg$$

$$q = \frac{mgd}{V}$$

$$= \frac{\left(4.80\times10^{-16}\,\text{kg}\right)\left(9.81\,\text{m/s}^2\right)\left(6.00\times10^{-2}\,\text{m}\right)}{\left(588\,\text{V}\right)}$$

$$= 4.804898\times10^{-19}\,\text{C}$$

Determine the number of electrons required to obtain the charge.

$$\#\,\text{electrons} = \frac{\text{charge}}{\text{elementary charge}}$$

$$= \frac{\left(4.804898\times10^{-19}\,\text{C}\right)}{\left(1.60\times10^{-19}\,\text{C}\right)}$$

$$= 3\,\text{electrons}$$

Paraphrase

The particle has three excess electrons.

SC. 3

No, it is not possible to have a charge of 2.00×10^{-19} C because it is not possible to have a quarter of an electron. It is only possible to have whole number multiples of 1.60×10^{-19} C; the charge must be 1.60×10^{-19} or 3.20×10^{-19} or 4.80×10^{-19} C, etc.

$$\#\,\text{electrons} = \frac{\text{charge}}{\text{elementary charge}}$$

$$= \frac{\left(2.00\times10^{-19}\,\text{C}\right)}{\left(1.60\times10^{-19}\,\text{C}\right)}$$

$$= 1.25\,\text{electrons}$$

Lesson 3

SC 1.

a. **Many** of the alpha particles pass by with little or no scattering, indicating the atom was mostly empty space.

b. **Few** of the alpha particles are scattered at large angles, indicating the presence of a small, dense nucleus.

c. On occasion, **rare** alpha particles are scattered straight back toward the source, indicating the presence of a very dense, positively charged nucleus. Presumably, a large electrostatic force of repulsion would be required to reverse the alpha particles' direction of motion.

SC 2. Both the emission and absorption spectral lines occur in the same place on the spectrum. This means that a gas can only absorb and emit the same, specific wavelengths of EMR.

SC 3.

Postulates That "Fit" Classical Physics	Postulates That "Fit" Quantum Physics
• Electrons orbit the nucleus. They are held in orbit by an electrostatic force.	• Electrons can only be in certain, permitted orbits and an electron does not emit radiation when it is in one of these orbits. • An electron only emits radiation when it "falls" from a higher energy state to a lower state.

SC 4. The initial incident photons are all projected in one direction through the atomic gas and onto the detector or screen. The photon absorbed by the electron and later released is scattered in a random direction, as shown in the diagram below. As a result, the dark lines are a very few photons re-emitted in that direction but the majority of the photons are emitted in different directions.
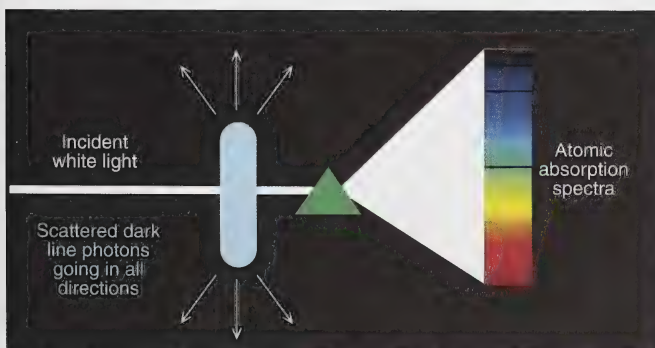
SC 5.

a.

region of
highest probability
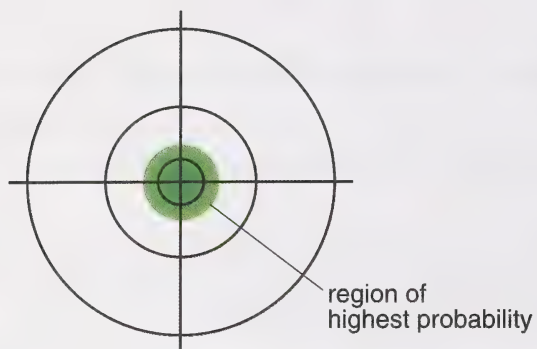
b. The quantum mechanical model is illustrated using a wide probability density cloud, but at a distance farther from the nucleus than the thin circular line of the Bohr model for the ground state.

SC 6.

a.
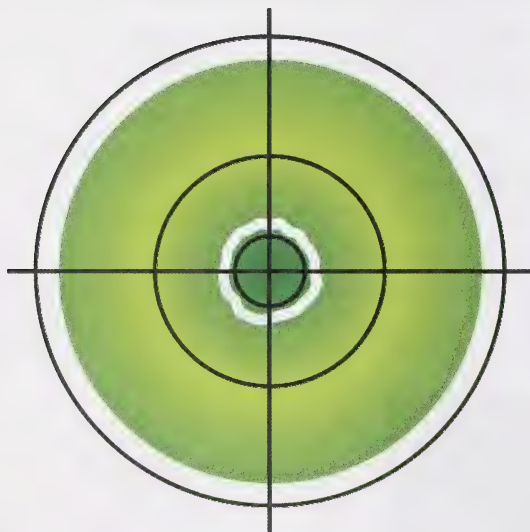
b. The quantum mechanical model is illustrated using a wide probability density cloud, whereas the Bohr model is illustrated by thin, circular lines.

Physics 30

Learn EveryWare

Nuclear Decay, Energy and the
Standard Model of the Atom

Module 8

Contents

Module 8—Nuclear Decay, Energy, and the Standard Model of the Atom

Module Introduction

In this module you will explore the nuclear world all the way down to the quarks that compose protons and neutrons. You will begin this journey at the edge of the nucleus by first understanding its composition and the forces that keep it together, as well as the energy that is associated with its decay and stability. These processes are applied in ionizing smoke detectors and radiometric dating.

Fission and fusion will be compared and contrasted in terms of changes to the number and type of nucleons that compose both parent and daughter material. They will also be described in terms of the large amount of energy associated with both reactions.

Next you will see how it is possible to probe the subatomic world in search of the fundamental particles that make up all of the subatomic particles, such as the proton and neutron. You will see how these investigations into antimatter, mediating particles, and quarks continue to inform the standard model, which describes current theory and models about the relationship between the fundamental forces and mediating particles. Your exploration will end, however, before the finish line as technology, theory, and model continue to evolve with new insight and evidence still being gathered in highly energetic laboratories around the world.

Specifically, you will be asked to apply your knowledge to answer the following questions:

- What is our current understanding of the atom?

- How do models, such as the standard model, evolve as new evidence and technology are applied at the atomic and subatomic levels?

Big Picture

The question marks on the balls in this photo represent the unknown. What do you suppose is inside each of them? How could you find out?

Now imagine they are so small that you can't even see them with an electron microscope, never mind an optical one. Imagine they are held together by the strongest fundamental force in the universe, yet sometimes they spontaneously break down into smaller balls.

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To study how they are arranged, you shoot other small balls at them and see how they scatter. Then you investigate the results when the balls spontaneously break down into smaller pieces. You apply this understanding to developing new and innovative technologies that can save lives, identify unknown chemicals, and generate enormous amounts of power.

The balls can be split apart and they can be fused together; and every ball has an opposite twin, what we would call its anti-ball. If any ball should ever meet its anti-ball, they would both be annihilated, releasing large amounts of energy.

With collisions of sufficient energy, the balls can be smashed open, revealing the inner particles. These inner particles can then be smashed again and again using higher and higher energy collisions to release the increasingly smaller, fundamental particles held together by incredible forces.

Along the way, theories and models evolve as you try to understand the composition of the balls and the fundamental forces that interact with them. Yet the question mark remains, symbolizing that you are still unable to verify all the parts in a theory that tries to capture the relationship between the fundamental particles of matter and the fundamental forces (such as gravity) that extend throughout the universe.

If you have not put it together already, the yellow balls represent atoms that are held together by a strong nuclear force. Atoms undergo alpha and beta decay and can release enormous amounts of energy when they split apart or fuse together. The regular matter that makes up these atoms is matched by antimatter, which will annihilate them if they meet. Massive particle accelerators are used to smash them, revealing protons that can be smashed again, revealing the fundamental quarks that make up hundreds of subatomic particles.

More experimentation and theory suggest the presence of other mediating particles thought to carry the fundamental forces, such as gravity and electromagnetism. Some of these particles have been observed, others have not; but, together, they all contribute to the ongoing investigation and understanding of what makes up matter.

By the end of Module 8 you will be able to describe the investigations and evidence that are part of the ongoing development of theories and models related to the fundamental structure of matter. As you are working in Module 8, you will explore the developing models of the atom in the context of the following questions.

- Which components make up the nucleus of an atom and what keeps them from coming apart?

- What are alpha and beta decay? How do they relate to the conservation of mass and energy?

- What is half-life and how does it relate to dating organic and inorganic material?

- Why are nuclear fission and fusion reactions so powerful?

- How is it possible to probe the subatomic world in search of the fundamental particles that make up protons and neutrons?

- How does the discovery of antimatter and subatomic particles inform the latest models concerning the structure of matter?

▼ Module Assessment

Each lesson has a teacher-marked assignment, based on work completed in the lesson. In addition, you will be graded on your contributions to the Discuss section of each lesson.

You will also be asked to complete Self-Check or Try This questions, which you should place in your Physics 30 course folder. These are not formally assessed but are a valuable way to practise the concepts and skills of the lesson. These activities can provide you with reflective feedback on your understanding of the lesson work.

You will be marked for your lesson work on the following items:

- Module 8: Lesson 1 Assignment
- Module 8: Lesson 2 Assignment
- Module 8: Lesson 3 Assignment
- Module 8: Lesson 4 Assignment

At the end of the module you will complete a module assessment that consists of two Diploma Exam-style written-response questions. The first question will assess your ability to apply the principles of conservation of mass-energy and conservation of momentum to a fusion reaction and the second question will assess your knowledge of decay curves and half-lives of radioactive elements. See the Module Summary and Assessment section towards the end of this booklet for more information. If you have any questions contact your teacher.

In This Module

Lesson 1—The Nucleus and Radioactive Decay

In this lesson you will explore the nucleus and the process of decay in technologies such as the ionizing smoke detector.

- What components make up the nucleus of an atom and what keeps them from coming apart?
- What are alpha and beta decay?
- How is the conservation of energy and mass applied to nuclear decay?

Lesson 2—Decay Rates and Radioactive Dating

In this lesson you will explore the concepts of half-lives and the rate of decay in relation to dating rocks and organic material.

- What is a half-life?
- How are half-lives used to determine age?

Lesson 3—Fission and Fusion

In this lesson you will compare and contrast the characteristics of fission and fusion reactions in the context of power generation and research.

- Why do nuclear reactions release so much energy?
- What is nuclear fission?
- What is nuclear fusion?

Lesson 4—The Subatomic World

In this lesson you will learn about ongoing developments that inform the standard model for the structure of matter.

- How is it possible to probe the subatomic world?

- Which subatomic particles make up the proton and neutron?

- How do the discovery of antimatter and subatomic particles inform the latest models concerning the structure of matter?

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Module 8—Nuclear Decay, Energy, and the Standard Model of the Atom

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Lesson 1—The Nucleus and Radioactive Decay

▽ Get Focused

The typical household ionizing smoke detector uses nuclear reactions to detect smoke in the air. Inside such a detector is a small amount of radioactive americium-241. During normal operation, the large nucleus of this isotope spontaneously emits alpha particles, which ionize the air molecules between two charged plates generating a constant current. When smoke particles enter the detector, they prevent the alpha particles from ionizing the air and the current drops, triggering the alarm circuit and audible noise to warn anybody nearby.

© Lilac Mountain/shutterstock

The amount of radioactive material in an ionizing smoke detector is very small. This makes it safe for prolonged household use. However, manufacturers recommend that they be replaced every 10 years because the radioactive material operating the detector will eventually be depleted. Radioactive materials, such as americium-241, naturally break down, or decay, leaving a smaller nucleus as alpha particles and gamma radiation are emitted. Why does this happen? What makes a nucleus unstable enough to break down and emit smaller particles?

In this lesson you will answer the following essential questions:

- Which components make up the nucleus of an atom and what keeps them from coming apart?
- What are alpha and beta decay?
- How is the conservation of energy and mass applied to nuclear decay?

▽ Module 8: Lesson 1 Assignment

Your teacher-marked Module 8: Lesson 1 Assignment requires you to submit responses to the following:

- Lab—LAB 1, LAB 2, LAB 3, and LAB 4
- Reflect and Connect—RC 1, RC 2, RC 3, RC 4, RC 5, RC 6, and RC 7
- Discuss—D 3

The other questions in this lesson are not marked by the teacher; however, you should still answer these questions. The Self-Check and Try This questions are placed in this lesson to help you review important information and build key concepts that may be applied in future lessons.

After a discussion with your teacher, you must decide what to do with the questions that are not part of your assignment. For example, you may decide to submit to your teacher the responses to Try This questions that are not marked. You should record the answers to all the questions in this lesson and place those answers in your course folder.

Explore

The Nucleus

What's in the nucleus of the atom? Recall from Module 7: Lesson 3 that the nucleus is very small compared to the entire volume of the atom. This fact was confirmed by Rutherford in his **alpha particle** scattering experiments. The nucleus is only about 10^{-14} m across, while the entire atom may be as much as 10 000 times wider. Even though it is very small, the nucleus makes up almost the entire mass of the atom. The large particles found inside the nucleus are called **nucleons**.

alpha particle: two protons and two neutrons bound together to form a stable particle identical to a helium nucleus

nucleon: a proton or neutron

proton: a positively charged particle found in all nuclei

neutron: a neutral particle found in the nucleus

There are two types of nucleons: **protons** and **neutrons**. Protons carry a charge of +1; neutrons have no net charge. In a neutral atom, the number of protons is always balanced by the number of electrons. An ion is created when there is an unequal number of protons and electrons, producing a net positive or negative charge.

The Periodic Table

The periodic table provides important reference information on each element. The periodic table is ordered by **atomic number,** the number of protons in the nucleus. An element is uniquely determined by the number of protons it has—an atom with 92 protons is uranium, regardless of the number of neutrons or electrons present. If protons are added or taken away, the element is no longer uranium.

atomic number (Z): the number of protons in the nucleus

The atomic number uniquely identifies the element.

atomic mass: the weighted mean atomic mass number of the element's natural isotopes

This number is given on the periodic table.

The number of neutrons in a nucleus is not given on the periodic table, although the **atomic mass** can be used to calculate the number of neutrons in the most common **isotopes**. The number of electrons in an atom is equal to the number of protons and is important for chemists. The number of electrons is important for beta-positive decay.

7

11 Na
22.99
sodium

In previous science courses you used the periodic table to calculate how many of each type of nucleon was in the nucleus. For example, the atomic mass of sodium, which is 22.99, was rounded to 23—the total number of nucleons. Because sodium has 11 protons (the atomic number), it must have 12 neutrons to add up to an atomic mass of 23.

The **atomic mass number** is the number of nucleons in the nucleus. If the atomic mass number of sodium is 23, why is the atomic mass on the periodic table 22.99?

isotope: an atom that has the same number of protons but a different number of neutrons and, therefore, a different atomic mass number

atomic mass number (A): the number of nucleons in an atom's nucleus

Isotopes

Different atoms of the same element may have different numbers of neutrons and therefore different atomic masses. Uranium nuclei, for example, have various masses due to variations in the number of neutrons. The various masses are called isotopes. Hydrogen exists in three isotopes, with the nuclei having zero, one, or two neutrons. There are many isotopes of uranium. The atomic mass value listed on the periodic table is the mean atomic mass of the element that is abundant in nature, which is the value used by chemists who deal with large numbers of atoms at a time. Physicists tend to deal with individual atoms so the isotope's atomic mass is indicated as a number after the element's name. For example, look at the following table.

Isotope	Name	Atomic Mass	Number of Protons	Number of Neutrons
H-1	Hydrogen 1	1	1	0
H-2	Hydrogen 2 (deuterium)	2	1	1
H-3	Hydrogen 3 (tritium) *unstable*	3	1	2

Isotopes of one element all have the same chemical properties, since they have the same number of protons. The nuclear stabilities may differ dramatically, however. Lead, for example, has 35 isotopes, only four of which are stable.

Symbolic Notation

Because of the various isotopes of an element such as hydrogen, the chemical symbol H does not provide sufficient information about the nucleus.

The Nuclide Symbol

$$_{Z}^{A}X$$

$$A = Z + N$$

Quantity	Symbol	SI Unit
atomic mass number— the number of nucleons	A	--
atomic number	Z	--
neutron number	N	--
chemical symbol	X	--

Using this notation, the three isotopes of hydrogen H-1, H-2 and H-3 are expressed as $_{1}^{1}H$, $_{1}^{2}H$, and $_{1}^{3}H$.

As demonstrated with hydrogen, isotopes can be written with the element name followed by the mass number as well as with nuclide symbols. For example, uranium-238 is the isotope $_{92}^{238}U$.

Self-Check

SC 1. How many neutrons are in lead-204?

Check your work with the answer in the appendix.

Try This

TR 1. Complete "Practice Problems" 1 and 2 on page 791 of your physics textbook.

The Atomic Mass Unit

The average mass of a hydrogen atom is 1.01. It is reported in atomic mass units (u), which are defined as exactly $\frac{1}{12}$ of the mass of the carbon-12 atom.

$1\ u = 1.660539 \times 10^{-27}\ kg$

The value for the atomic mass unit was determined using a mass spectrograph, which is very similar to J.J. Thomson's charge-to-mass ratio experiment you studied in Module 7: Lesson 1.

Try This

TR 2. A singly ionized carbon atom is accelerated by a parallel-plate apparatus and passes through a velocity selector with a magnetic field strength of 0.950 T and an electric field strength of 5.60×10^5 V/m. The ion then passes into a mass spectrograph with a magnetic field of 1.50 T and the sensor detects a radius of 4.89×10^{-2} m.

    a.   What is the velocity of the carbon ion as it passes through the velocity selector?
    b.   What is the mass of the carbon ion as determined by the mass spectrograph?
    c.   If the carbon ion has an atomic mass of 12, what is the value of 1 atomic mass unit?

Read

The preceding information can also be found in your physics textbook on pages 790 and 791. "Table 16.1" on page 792 lists the masses of subatomic particles in both kilograms (kg) and atomic mass units (u).

Nuclear Decay

There is one question about the nucleus that has yet to be addressed. If the nucleus is a ball of positively charged protons, why don't these like charges fly apart? Recall from Module 3: Lesson 2 that Coulomb's law of electrostatic forces would indicate that the positive protons should repel each other, leading to a breakdown of the nucleus. In fact, some atoms do break down because of this electrostatic force. This is called **nuclear decay**.

So, while there is evidence of some nuclear decay, what stops the atom from totally breaking apart from repelling protons?

Nuclear Forces

The nucleus is held together by what physicists call the strong nuclear force. This fundamental force of nature counters the electrostatic force of repulsion that would exist between the protons in the nucleus. For example, the gravitational attraction between two protons 5 cm apart is 7 $\times 10^{-36}$ N, while the electrostatic force of repulsion at the same distance is 9 N. Just making up the difference

The four fundamental forces are as follows:

1. gravitational force
2. electromagnetic force
3. weak nuclear force
4. strong nuclear force

between these two fundamental forces would require a nuclear force that is 10^{37} times stronger than gravity. The strong nuclear force is massive compared to the gravitational force; but the gravitational force extends throughout the universe, whereas the strong nuclear force can act only over distances that are—relative to the size of the nucleus ($\sim 10^{-14}$ m)—extremely small.

So, why are some atoms stable and others unstable? And what is the purpose of all these neutrons? The strong nuclear force is almost independent of electric charge but acts only over a very short distance. It exists between any nucleon pair, whether it's a proton-proton, neutron-neutron, or proton-neutron. Even though the strong nuclear force is powerful, the electrostatic repulsive force has a longer range of action. This means that one proton is repelled by every other proton in the nucleus but is attracted only to its nearest neighbours.

Force	Relative Strength	Range
strong nuclear	1	$\approx 10^{-14}$ m (nucleus)
electromagnetic	0.0073	∞
weak nuclear	10^{-9}	$\approx 10^{-18}$ m (nucleon)
gravitational	10^{-38}	∞

As protons are added to a nucleus (moving down in the periodic table to heavier elements), more neutrons need to be added to balance out the additional repulsive electrostatic forces. At some point, however, adding neutrons no longer helps. All nuclei with more than 83 protons are unstable and will decay spontaneously, like americium-241 in the smoke detector, which has 95 protons.

Try This

Complete "Practice Problems" 1 and 2 on page 792 of the textbook.

Scientists working with radioactive substances discovered that helium gas was invariably present in their experiments. Rutherford proposed that the helium gas was produced by the radioactive substances and that the alpha particle, known to be produced by radioactive materials, was simply a helium nucleus missing its electrons. When Rutherford experimented with radon, he found that radon spontaneously split into an alpha particle (a helium nucleus) and a polonium atom. This natural change from one element to another is called **transmutation**. The original element is known as the **parent element** and the new element is called the **daughter element**.

> **transmutation:** decay or change into a different element
>
> **parent element:** the original element in a decay process
>
> **daughter element:** the element produced by a decay process

Watch and Listen

Go to the Physics 30 Multimedia DVD and watch "Natural Transmutations/Decay Animation," which is an animation of the parent carbon-14 decay into the daughters nitrogen-14, electron, and electron antineutrino.

Since the transmutation of radon to polonium produced an alpha particle, it is called alpha decay. If the particle emitted is a beta particle, it is called beta decay. The term *decay* refers to a larger particle splitting into smaller particles.

Reflect and Connect—Three Types of Nuclear Radiation

Rutherford classified the three types of naturally occurring nuclear radiation according to penetrating ability. Listed from least to greatest penetrating ability, the three types are alpha, beta, and gamma rays.

When americium-241 decays, it releases alpha particles energetic enough to ionize gas molecules. This fact is used in the ionizing smoke detector where ionized gas molecules are used as conductors between two electrodes, establishing a current in the detector. When smoke particles enter the detector they block the alpha particles, which stops the ionization of the air causing the current in the gas to drop, triggering the alarm.
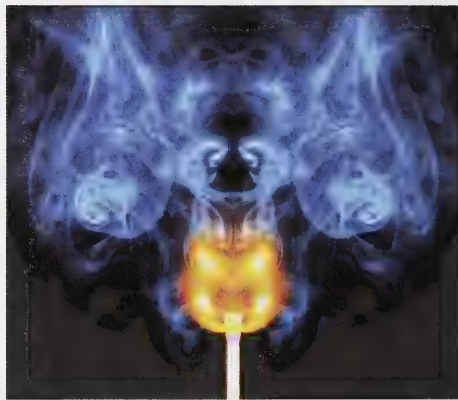
© ANP/shutterstock

You can explore the effect that smoke and other barriers have on radiation using a Geiger counter, a device that measures the number of alpha particles, beta particles, and gamma radiation emitted by an isotope. Either the type of barrier or the radioactive isotope can be manipulated. The responding variable is the amount (per unit time) of each type of radiation reaching the Geiger counter.

Go to the Physics 30 Multimedia DVD and open the "Geiger Counter Simulation." This simulation uses a Geiger counter to measure the number of alpha and beta decay particles emitted from an isotope in a five-second time interval.

? Module 8: Lesson 1 Assignment

Go to the Module 8 Assignment Booklet and complete RC 1, RC 2, RC 3, RC 4, RC 5, RC 6, and RC 7. You will be using the "Geiger Counter Simulation" from the Physics 30 Multimedia DVD for these Reflect and Connect questions.

Try This

TR 4. Read the description of each particle below, and explain why Rutherford's ranking of emitted radiation particles by penetrating power makes sense in terms of the structure of each particle.

- alpha (α) particle: a helium nucleus made up of 2 neutrons and 2 protons; symbol ^4_2He or $^4_2\alpha$

- beta (β) particle: a very high-speed electron; symbol $^{\ 0}_{-1}\text{e}$ or $^{\ 0}_{-1}\beta$

- gamma (γ) particle: a high-energy photon (higher energy than X-rays); symbol $^0_0\gamma$

The Process of Nuclear Decay

The decay process must obey the following laws of physics:

1. conservation of charge
2. conservation of nucleons
3. conservation of mass-energy

Beta Decay

Rutherford observed beta-negative decay, the emission of an electron from a nucleus. Beta-positive decay was observed later (the emission of a positron).

The first two laws will be used to complete and balance nuclear decay equations while the third will be applied later when you investigate the concept of mass defect and binding energy.

There are several types of decay that can be simulated with the "Nuclear Decay Gizmo," which you should open on the Physics 30 Multimedia DVD now. Use the gizmo to study alpha and beta decay. Watch for the concepts of conservation of charge and nucleon number as you complete the following activity. Activate the animation on the lower right of the graphic.

Alpha Decay (α)

The alpha decay of uranium-238 can be represented with an equation and animation. The default display for the "Nuclear Decay Gizmo" is for the alpha decay of a uranium-238 nucleus.

Module 8: Lesson 1 Assignment

Go to the Module 8 Assignment Booklet and complete LAB 1 and LAB 2.

In LAB 2 you observed uranium-238 as the parent element and thorium-234 as the daughter element.

> According to the conservation laws, alpha decay can be represented by the following equation.
>
> $$_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}Y + {}_{2}^{4}\alpha$$
>
> | Quantity | Symbol | SI Unit |
> |---|---|---|
> | X – parent element | X | -- |
> | Y- daughter element | Y | -- |
> | α- alpha particle | α | $_{2}^{4}He$ |
>
> The atomic mass number (A) and the atomic number (Z) are conserved in nuclear decay reactions.
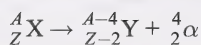
Example Problem 1. Use the americium-241 from the smoke detector to answer the following questions.

a. What is the alpha decay equation?

$$_{95}^{241}Am \rightarrow {}_{93}^{237}Np + {}_{2}^{4}\alpha$$

or

$$_{95}^{241}Am \rightarrow {}_{93}^{237}Np + {}_{2}^{4}He$$
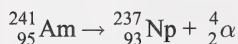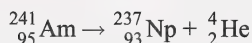
b. What is the parent element and what are the daughter elements?

The parent element is americium-241. The daughter elements are neptunium-237 and helium-4.

c. How does this decay equation obey the law of conservation of charge?

The law of conservation of charge is obeyed because there are 95 protons before the transmutation and 95 protons (93+2) after the transmutation. Electrons are not involved in this transmutation.

d. How does this decay equation obey the law of conservation of nucleons?

The law of conservation of nucleons is obeyed because there are 241 nucleons before the transmutation and 241 nucleons (237+4) after the transmutation.

⚠ Try This

Complete "Practice Problems" 1 to 3 on page 800 of your physics textbook.

Beta Decay (β)

The beta decay of carbon-14 can be represented with an equation and animation. Go back to the Physics 30 Multimedia DVD and open the "Nuclear Decay Gizmo" and change the "type of decay" to "beta decay."

❓ Module 8: Lesson 1 Assignment

Go to the Module 8 Assignment Booklet and complete LAB 3 and LAB 4.

In LAB 3, you observed carbon-14 as the parent element and nitrogen-14 as the daughter element.

In beta-negative decay, a neutron converts into a proton, electron, and **antineutrino**. The proton is retained by the nucleus, keeping the atomic mass constant while increasing the atomic number and, thus, changing the type of element. The emitted electron is called a beta particle to distinguish it from the electrons around the nucleus. According to the conservation laws, beta decay can be represented by the following equation.
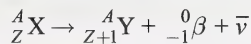
$$_Z^A X \rightarrow _{Z+1}^A Y + _{-1}^0 \beta + \bar{v}$$

Quantity	Symbol	SI Unit
X – parent element	X	--
Y - daughter element	Y	--
β - beta particle	β	$_{-1}^0 e$
$\bar{v}$ - antineutrino	$\bar{v}$	--

atomic mass number (A) and the atomic number (Z) are conserved in nuclear decay reactions

The **antineutrino** listed in the preceding equation was not included in the simulation.

![Read icon] **Read**

Read about the **neutrino** on page 804 of the textbook.

antineutrino: $\bar{v}$, a tiny subatomic particle with no charge emitted with $_{-1}^{0}e$ in beta decay.

neutrino: v, a tiny subatomic particle with no charge emitted with a positron in beta-positive decay

Example Problem 2. Amercium-241 is produced by a beta decay of plutonium-241.

1. Write the beta decay reaction for plutonium-241.

   $$_{94}^{241}Pu \rightarrow {}_{95}^{241}Am + {}_{-1}^{0}\beta + \bar{v}$$

   or

   $$_{94}^{241}Pu \rightarrow {}_{95}^{241}Am + {}_{-1}^{0}e + \bar{v}$$
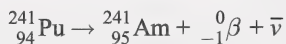
2. What is the parent element and what are the daughter elements?

   The parent element is plutonium-241. The daughter element is americium-241. (Electrons and antineutrinos are not elements.)

3. How does this decay equation obey the law of conservation of charge?

   The law of conservation of charge is obeyed because there are 94 protons before the transmutation and after there are 95 protons in the americium but negative one on the electron [95+ (−1) = 94]. [A neutron ($q = 0$) changes into a proton ($q = 1$) and an electron ($q = -1$).]

4. How does this decay equation obey the law of conservation of nucleons?

   The law of conservation of nucleons is obeyed because there are 241 nucleons before the transmutation and 241 nucleons after the transmutation. (The beta particle and the antineutrino are ejected from the americium 241 atom.)

![Try This icon] **Try This**

TR 6. Complete "Practice Problem" 1 with Example 16.8 and "Practice Problem" 1 with Example 16.9 on page 803 of your physics textbook. Remember that each reaction also produces a beta particle and an antineutrino.

Read

Read about **antimatter** and the **positron** on pages 804 and 805 of the textbook. Note in Example 16.10 the extra electron that must be taken into account in the mass defect.

Self-Check

SC 2. How does the weak nuclear force relate to beta decay (both positive and negative decay)?

antimatter: a form of matter that has properties opposite to its normal-matter counterpart

positron: the antimatter to an electron

It is the same type of particle but has an opposite charge. Unlike electrons, positrons are scarce.

Check your work with the answer in the appendix.

In beta-positive decay, a proton converts into a neutron and a positron. The neutron is retained by the nucleus, keeping the atomic mass constant while decreasing the atomic number and thus changing the type of element. The beta particle emitted is called a positron. According to the conservation laws, beta-positive decay can be represented by the following equation.

Note: the parent atom has Z electrons to be electrically neutral, when the proton changes into a neutron and positron there is $Z-1$ electrons in the daughter nucleus. An electron is released to drift away but this is not shown in the equation. This will affect the mass defect equations you will see later.

$$_Z^A X \rightarrow {}_{Z-1}^A Y + {}_1^0 \beta + v$$
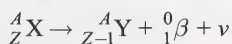
Quantity	Symbol	SI Unit
X – parent element	X	--
Y- daughter element	Y	--
$_1^0\beta$ - beta particle (positron)	β	$_1^0\beta$
$\bar{v}$ - neutrino	v	--

atomic mass number (A) and the atomic number (Z) are conserved in nuclear decay reactions

---

Example Problem 3. Write the beta-positive decay equation for nickel-56.

$$_{28}^{56}\text{Ni} \rightarrow {}_{27}^{56}\text{Co} + {}_1^0\beta + v$$

The Neutrino and Antineutrino

The neutrino and antineutrino are a matter-antimatter pair. The existence of an antineutrino was hypothesized when the kinetic energy of a beta particle following beta decay was lower than expected. It was predicted that some other particle was carrying this energy away before the particle could be detected. This was later proven to be true.

Gamma Decay (γ)

Often, the alpha and beta decay processes leave the daughter nucleus in an excited state, with the nucleons spread apart. Similar to that of an electron in an energy level, the nucleons will rearrange to form a more stable ground state and releases very high frequency gamma radiation as a result.

According to the EMR spectrum, gamma radiation has extremely high energy, which corresponds to a high frequency and a short wavelength. It has no mass or charge, therefore producing no changes in the atomic number or atomic mass of the nucleus. There is no transmutation with the emission of gamma radiation. Gamma rays are represented by the symbol (γ).

The nucleus may be left in an excited state after alpha or beta decay. In the nuclear equation, this excited state is represented with an asterisk (*). The nucleus then experiences gamma decay to return to a ground state.

Read

Read pages 806 and 807 of your physics textbook for an example of a gamma decay chain and equation as well as a radioactive decay series.

Decay Series

Many of the daughter nuclei produced by alpha and beta decay are still unstable and, as such, will undergo further transmutation. In such cases a **decay series** is used to illustrate the successive decays until a stable nucleus is produced. Search the Internet for examples of decay series. In most, each dot in this series represents a new nucleus. Both alpha and beta decay form part of each series as the parent material undergoes successive decay in both forms until a stable nucleus is reached.

The Direction of Alpha and Beta Decay in the Diagram
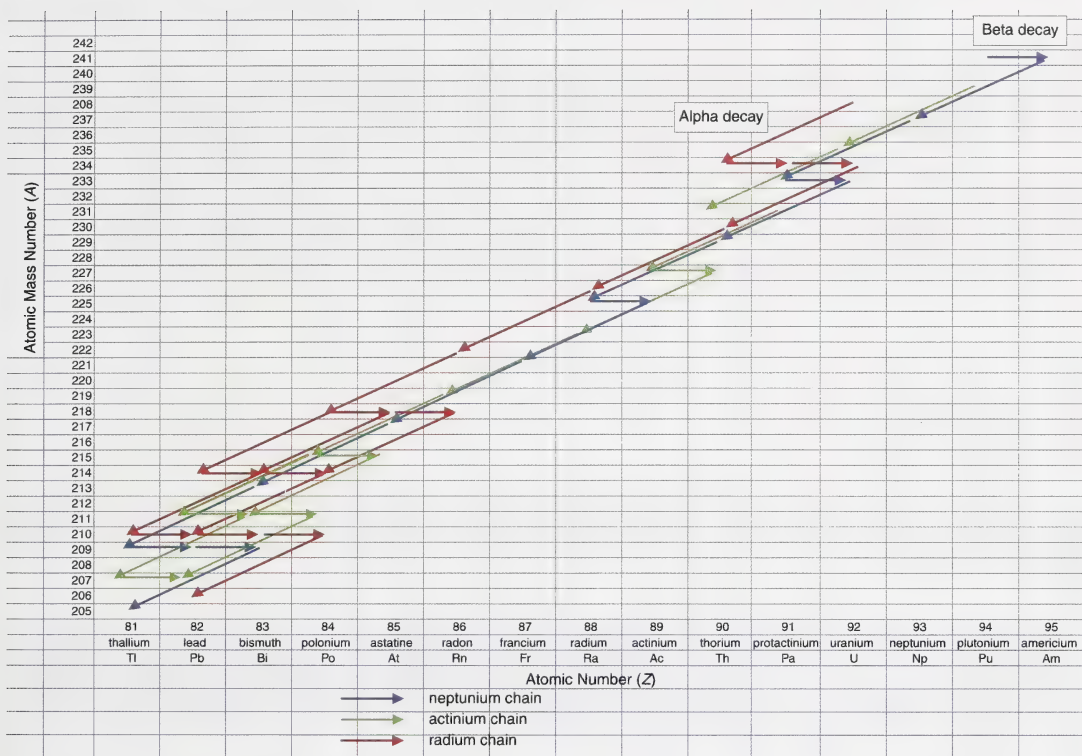
First, focus on why alpha and beta decay are drawn in the direction shown. Recall that alpha decay (the release of a ^4_2He nucleus) involves a decrease in atomic mass number (by four) and a decrease in protons (by two). On the chart, therefore, you need to move down four and left two to get to the new mass number and atomic number.

Notice on page 807 of your physics textbook that the alpha decays are red arrows. Also notice that the horizontal axis increases by one atomic number and the vertical axis increases by four atomic mass numbers per line.

Beta decay results in no change to the atomic mass number, so there is no movement up or down on the grap; but it results in an increase in the atomic number, so there is a movement of one unit to the right. Still on page 807 of the textbook, notice that a horizontal blue arrow that is two units long must, therefore, represent two beta decays in succession.

Example Problem 4. Using the decay series on page 807 of your textbook, write the nuclear decay equations that represent the transmutation of protactinium-234 to radium-226 (from the radium decay series).

Find the dot for protactinium-234, and read off the chemical symbol and atomic number, $^{234}_{91}\text{Pa}$. Do the same for its daughter element, $^{234}_{92}\text{U}$ (uranium-234 in this case). Set up the nuclear equation; then use the concepts of conservation of charge and nucleons to balance the equation by adding either an alpha particle or beta particle. (You could just add the particle by referring to the decay type shown in the diagram; but you should still check that the equation is balanced.) If the decay is beta, remember to add the antineutrino.

Continue to follow the decay chain in this way until all of the equations have been written.

$$^{234}_{91}\text{Pa} \rightarrow \, ^{234}_{92}\text{U} + \, ^{0}_{-1}\beta + \bar{v}$$
$$^{234}_{92}\text{U} \rightarrow \, ^{230}_{90}\text{Th} + \, ^{4}_{2}\alpha$$
$$^{230}_{90}\text{Th} \rightarrow \, ^{226}_{88}\text{Ra} + \, ^{4}_{2}\alpha$$
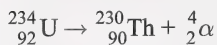
Try This

TR 7. Using the neptunium decay series in the decay series diagram above, trace the decay from uranium-233 to francium-221. Write the nuclear equations that represent this series of transmutations.

The Release of Energy During Nuclear Decay

A significant amount of energy is released during transmutations, which is clearly evident from the kinetic energy of the released alpha or beta particle. Einstein developed the equation for mass-energy equivalency the famous $E=mc^2$. During a transmutation, a small amount of mass is changed directly into energy. This can easily be shown by calculating the mass of a uranium-235 atom from its constituent parts.

$$92 \text{ protons} \rightarrow 92 \times 1.67 \times 10^{-27} \, \text{kg} = 1.5364 \times 10^{-25} \, \text{kg}$$
$$143 \text{ neutrons} \rightarrow 143 \times 1.67 \times 10^{-27} \, \text{kg} = 2.3881 \times 10^{-25} \, \text{kg}$$
$$92 \text{ electrons} \rightarrow 92 \times 9.11 \times 10^{-31} \, \text{kg} = 8.3812 \times 10^{-29} \, \text{kg}$$
$$= 3.92533812 \times 10^{-25} \, \text{kg}$$

Note: The mass of the electrons is insignificant compared to the nucleons and is normally omitted.

$$\text{atomic mass} = \frac{3.92533812 \times 10^{-25} \, \text{kg}}{1.66 \times 10^{-27} \, \text{kg/u}}$$
$$\text{atomic mass} = 236.4661518 \, \text{u}$$
$$\text{atomic mass} = 236 \, \text{u}$$

So from your calculations, the atomic mass of uranium-235 should be 236 u. If you look it up in "Table 7.5" on page 881 of the physics textbook, you will find that it is actually 235.043 930 u. Why is there a difference? Where did the lost mass go?

The lost mass is called the mass defect—the mass has been changed into binding energy holding the nucleons together. This mass defect is where the energy for nuclear reactions comes from and explains where the strong nuclear force to hold the atom together comes from.

The law of conservation of energy was violated by this discovery as energy appears to be created. Therefore, the law has been amended to the law of conservation of mass-energy, since Einsten showed that mass and energy are equivalent. In fact, particle physicists often don't bother with masses but use mass equivalent as measured in MeV/c^2.

$$\text{Mass defect} = \text{mass products} - \text{mass reactants}$$

It is possible to calculate the amount of energy released in a nuclear reaction by comparing the mass of the parent versus the daughter particles.

Einstein's Mass–Energy Equivalence		
$E = mc^2$		
Quantity	Symbol	SI Unit
energy released in a nuclear reaction per decay	E	J not eV
mass defect—the mass converted to energy in a nuclear reaction = $m_{products} - m_{reactants}$	m	kg
speed of light in a vacuum	c	m/s

Example Problem 5. What is the energy released when americium-241 transmutes?

From earlier we know the equation:

$$^{241}_{95}\text{Am} \rightarrow \, ^{237}_{93}\text{Np} + \, ^{4}_{2}\alpha$$

or

$$^{241}_{95}\text{Am} \rightarrow \, ^{237}_{93}\text{Np} + \, ^{4}_{2}\text{He}$$
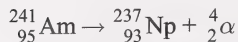
mass defect = mass products − mass reactants

$$\Delta m = m_{\text{p}} - m_{\text{r}}$$
$$\Delta m = (237.048167 \text{ u} + 4.002603 \text{ u}) - (241.056823 \text{ u})$$
$$\Delta m = -0.006053 \text{ u}$$
$$\Delta m = (-0.006053 \text{ u})\left(1.66 \times 10^{-27} \text{ kg/u}\right)$$
$$\Delta m = -1.004798 \times 10^{-29} \text{ kg}$$

The masses were obtained from NIST, National Institute of Standards and Technology.

$$E = mc^2$$
$$E = \left(1.004798 \times 10^{-29} \text{ kg}\right)\left(3.00 \times 10^{8} \text{ m/s}\right)^2$$
$$E = 9.04 \times 10^{-13} \text{ J}$$

The transmutation of one americium-241 atom releases 9.04×10^{-13} J.

Self-Check

SC 3. a. What is the beta-positive decay reaction for sodium-22?

b. What is the energy released by the beta-positive decay of sodium-22?

Check your work with the answers in the appendix.

Try This

TR 8. Complete "Practice Problems" 1 to 3 on page 801 of your physics textbook. The masses can be found in "Table 7.5" on page 881 of the textbook.

Read

Read "Conservation Laws and Radioactive Decay" on page 798 of the textbook for an overview of the laws obeyed in nuclear reactions.

Try This

TR 9. Complete "Practice Problem" 1.(b) on page 803 of your physics textbook. You have already completed 1.(a) as TR 6.

Discuss

Marie and Pierre Curie studied radioactivity before it was known to be dangerous to living systems. As a result both suffered from radiation sickness and some of Marie's lab notebooks are still dangerously radioactive today. Radiation sickness was also well documented among the survivors of the Hiroshima nuclear bomb (dropped August 6, 1945) and the Chernobyl reactor explosion (April 26, 1986).

© Postnikova Kristina/shutterstock

The potential hazards of nuclear radiation are now understood and we know that precautions must be taken to protect living tissue from damage caused by radiation.

Research radiation sickness related to both of these disasters. Also see pages 808 and 809 of the textbook for information required to answer the following questions in the discussion forum.

D 1. Answer the following questions on nuclear radiation:

- What is radiation sickness? How does radiation cause damage to living tissue? Use the following vocabulary in your response: ionization/ionize, and chromosomes/genetic material.

- Which type of radiation is most dangerous and why?

- Contrast ionizing and non-ionizing radiation. Include real-life applications of each type.

- How is radiation exposure measured? How much is deemed safe?

- Where else in this course have we seen forms of ionizing radiation?

D 2. Post your summary to the discussion area set up by your teacher. Compare your summary to at least one other explanation produced by another student. Identify similarities and differences between your work and the work of other students. Remember to add the answer to this question to your course folder.

Module 8: Lesson 1 Assignment

Go to the Module 8 Assignment Booklet and complete D 3.

See the Discussion Scoring Guide in the appendix.

Lesson Summary

In this lesson you focused on the following questions:

- Which components make up the nucleus of an atom and what keeps them from coming apart?
- What are alpha and beta decay?
- How is the conservation of energy and mass applied to nuclear decay?

The nucleus is very small, only about 10^{-14} m across, but it makes up nearly the entire mass of the atom. The nucleus is composed of smaller particles called nucleons. The protons and neutrons are both nucleons. The number of protons defines the element. The physical characteristics, such as atomic mass, vary due to the number of neutrons present. Two atoms, each with an identical number of protons but a different number of neutrons, are called isotopes. Each isotope has a unique atomic mass. The atomic mass unit (u) is defined as exactly $\frac{1}{12}$ of the mass of the carbon-12 atom (1 u = 1.66×10^{-27} kg).

The nucleus is held together by what physicists call the strong nuclear force, which must be overcome to change the number of nucleons in the atom.

Some nuclei are unstable and decay. This natural change from one substance to another is called transmutation. Alpha decay is defined by the production of an alpha particle ($_{2}^{4}\text{He}$) during the decay of a parent nucleus into a daughter nucleus. The general equation for alpha decay is $_{Z}^{A}\text{X} \rightarrow \, _{Z-2}^{A-4}\text{Y} + \, _{2}^{4}\alpha$.

Beta decay is defined by the production of a beta particle ($_{-1}^{0}\text{e}$) during the transmutation. The general equation for beta decay is $_{Z}^{A}\text{X} \rightarrow \, _{Z+1}^{A}\text{Y} + \, _{-1}^{0}\beta + \overline{v}$. Beta-positive decay is defined by the production of a positron ($_{-1}^{0}\text{e}$) (antimatter electron) during transmutation. The general equation for beta-positive decay is $_{Z}^{A}\text{X} \rightarrow \, _{Z-1}^{A}\text{Y} + \, _{1}^{0}\beta + v$.

In all three decay processes, charge and atomic mass number are conserved. Mass itself (atomic mass units, grams or kg) is not conserved, since in each process some mass is converted to energy according to the relationship $E = mc^2$.

All transmutations produce significant amounts of energy in the form of kinetic energy of the emitted particles and sometimes the production of high frequency gamma radiation. Einstein's mass-energy equivalency ($E = mc^2$) relates the mass defect in transmutations to the amount of energy released. Comparing these values supports the conservation of energy principle.

The alpha, beta, and gamma particles are a form of ionizing radiation. Ionizing radiation is dangerous because it has enough energy to ionize DNA and change chromosomes, which can lead to cancer or, in high doses, radiation sickness and death.

Lesson Glossary

antimatter: a form of matter that has properties opposite to its normal-matter counterpart

antineutrino: a tiny subatomic particle with no charge emitted with $_{-1}^{0}e$ in beta decay

alpha particle: two protons and two neutrons bound together to form a stable particle identical to a helium nucleus

atomic mass: the weighted mean atomic mass number of the element's natural isotopes

This number is given on the periodic table.

atomic mass number (A): the number of nucleons in an atom's nucleus

atomic number (Z): the number of protons in the nucleus

The atomic number uniquely identifies the element.

beta particle: an electron emitted by the nucleus when a neutron splits into a proton and electron during the beta decay process

daughter element: the element produced by a decay process

isotope: an atom that has the same number of protons but a different number of neutrons and, therefore, a different atomic mass number

nucleon: a proton or neutron

neutrino: a tiny subatomic particle with no charge emitted with a positron in beta-positive decay

neutron: a neutral particle found in the nucleus

parent element: the original element in a decay process

positron: the antimatter to an electron

It is the same type of particle but has an opposite charge. Unlike electrons, positrons are scarce.

proton: a positively charged particle found in all nuclei

transmutation: decay or change into a different element

Lesson 2—Decay Rates and Radioactive Dating

Get Focused

Heading west on Highway 3 near the Crowsnest Pass, you will find one of Alberta's most famous and most photographed trees. This limber pine, called the Burmis Tree, is more than 300 years old. It was a seedling in the late 1600s and died in 1978. It toppled over 20 years later in 1998. It has since been restored to its original position and is symbolic of the resiliency needed to survive in the unforgiving environment of the eastern Rocky Mountain slopes of Alberta.

The appeal of this natural landmark is its extreme age. Its gnarled branches have withstood more than 300 Alberta winters and countless days of high winds, drought, intense heat, and chilling cold. How could you know that this tree really is that old? How could you know when, and for how long, a tree has lived? How could you accurately determine when it died?

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The Burmis Tree, Crowsnest Pass, Alberta

The unstable nuclei of the carbon isotopes in the tree, or any carbon-based organism, provide a built-in clock that can be observed to determine its age. When the tree was alive, the process of photosynthesis extracted radioactive carbon-14 from the atmosphere and fixed it into the tissue of the tree. When it died, the process stopped. As you observed in Module 8: Lesson 1, the carbon-14 nuclei will undergo beta decay to form nitrogen-14. Due to this decay, the amount of carbon-14 in the tissue decreases over time. By comparing the current amount of carbon-14 in the tissue to that of the carbon-14 that was present when the organism formed, it is possible to determine an age. Of course, this is only possible if you first know how fast, or at what rate, the carbon-14 nuclei in the tree decayed.

In Lesson 2 you will explore the rate of decay and its application in radioactive dating.

In this lesson you will focus on answering the following essential questions:

- What is a half-life?
- How are half-lives used to determine age?

? Module 8: Lesson 2 Assignment

Your teacher-marked Module 8: Lesson 2 Assignment requires you to submit responses to the following:

- Lab—LAB 1, LAB 2, LAB 3, LAB 4, LAB 5, LAB 6, LAB 7, LAB 8, and LAB 9
- Reflect and Connect—RC 1 and RC 2

The other questions in this lesson are not marked by the teacher; however, you should still answer these questions. The Self-Check and Try This questions are placed in this lesson to help you review important information and build key concepts that may be applied in future lessons.

After a discussion with your teacher, you must decide what to do with the questions that are not part of your assignment. For example, you may decide to submit to your teacher the responses to Try This questions that are not marked. You should record the answers to all questions in this lesson and place those answers in your course folder.

Explore

Half Life

The **half-life** of a radioactive isotope is defined as the amount of time it takes for half of the radioactive particles to decay. Consider a container with 128 unstable nuclei.

half-life: the time it takes for half the radioactive nuclei in a sample to decay

Over time, some of the nuclei decay, forming daughter nuclei and related decay particles. Eventually, half of the nuclei will have decayed into daughter nuclei. In this example, after a certain amount of time had passed, 64 nuclei decayed to daughter nuclei, leaving 64 of the original parent nuclei.

The amount of time it takes for this to happen is defined as the half-life of the unstable parent nuclei. The half-life of other nuclei will be different. For example carbon-14, which is used to date organic material, has a half-life of 5730 years. While iodine-131, used in the medical diagnosis of thyroid problems, has a half-life of 192 hours.

Think About It

With such a short half-life, any iodine-131 found today was not around when Earth was formed.

? Module 8: Lesson 2 Assignment

Go to the Module 8 Assignment Booklet and complete LAB 1, LAB 2, LAB 3, LAB 4, LAB 5, LAB 6, and LAB 7. To complete these questions, you will use a simulation to explore the rate of radioactive decay and the concept of half-life. Go to the Physics 30 Multimedia DVD and open the "Half-life Simulation." Use the controls on the right side of the simulation to activate the animation.

The mathematical expression for the graph of parent nuclei versus time gives the following equation for determining the number of original parent nuclei in a radioactive sample after a given time interval.

$$N = N_0 \left(\frac{1}{2}\right)^n$$

Quantity	Symbol	SI Unit
amount of parent material remaining	N	activity/percentage/mass decay/second
amount of parent material at the start	N_0	activity/percentage/mass decay/second
number of half-lives elapsed	$n = \dfrac{t}{t_{1/2}}$	unitless
time	t	seconds/hours/days/years
half life	$t_{1/2}$	seconds/hours/days/years

Activity is usually measured in decays per second, or becquerels (Bq); however, mass and percentages can also be used to indicate the relative amount of parent material. Since these units appear on both sides of the equation, they will mathematically cancel one another.

Graphical representation of radioactive decay.
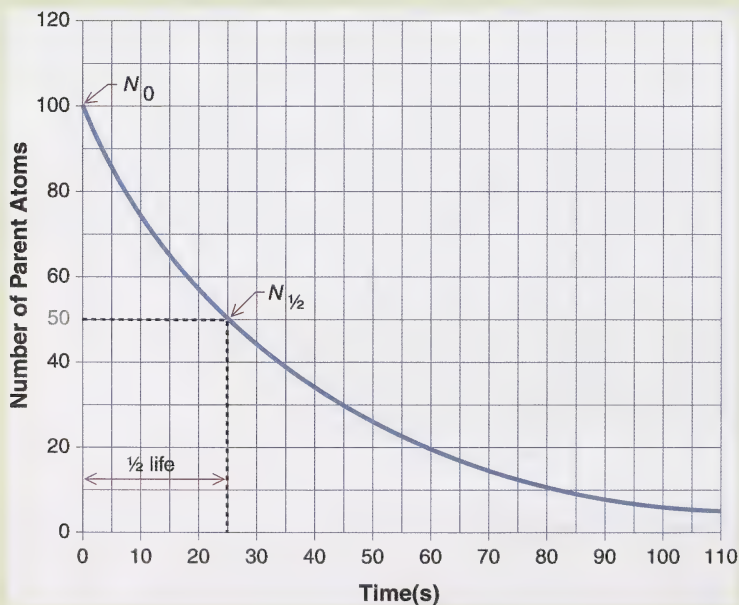
The half-life can be measured from the time axis from the point where half of the nuclei have transmuted. In this case, 50 nuclei are left after 25 seconds.

Example Problem 1. A radioactive sample has an activity of 3.2×10^3 Bq. The isotopes in the sample have a half-life of 24 hrs. What will be the activity of this sample after five days have passed?

Given

$t = 5$ d

$t_{1/2} = 1$ d

$N_0 = 3.2 \times 10^3$ Bq

Required

the amount of activity after five days

Analysis and Solution

Determine the number of half-lives that have elapsed.

$$n = \frac{t}{t_{1/2}}$$

$$= \frac{5 \text{ d}}{1 \text{ d/half life}}$$

$$= 5 \text{ half lives}$$

Determine the amount remaining.

$$N = N_0 \left(\frac{1}{2}\right)^n$$

$$= \left(3.2 \times 10^3 \text{ Bq}\right)\left(\frac{1}{2}\right)^5$$

$$= 1.0 \times 10^2 \text{ Bq}$$

Paraphrase

After five days, the sample will have an activity of 1.0×10^2 Bq.

Try This

TR 1. Complete "Practice Problem" 2 on page 813 of the textbook.

TR 2. Complete "Practice Problems" 1 and 2 on page 814 of the textbook.

Radioactive Dating

Using nuclear decay to determine age is only possible because radioactive decay is a predictable process. It can be used to determine the age of rocks, fossils, and artifacts. This method is called radiometric dating.

Module 8: Lesson 2 Assignment

Go to the Module 8 Assignment Booklet and complete LAB 8. You will need the "Half-life Simulation" from the Physics 30 Multimedia DVD to complete the question.

Summary

The isotopes that are useful for measuring the age of rocks and fossils have very long half-lives. As previously mentioned, the carbon-14 used to date organic material has a half-life of 5730 years, while uranium-235, used to date rocks, has a half-life of 704 million years.

Module 8: Lesson 2 Assignment

Go to the Module 8 Assignment Booklet and complete LAB 9. You will need the "Half-life Simulation" from the Physics 30 Multimedia DVD to complete the question.

Read

Read "Radioactive Decay Rates" on pages 811 to 816 of your physics textbook.

Self-Check

SC 1. The half-life of strontium-90 is 28 years. If 60 g of strontium-90 is currently in a sample of soil, how much will be in the soil in 84 years?

SC 2. The half-life of strontium-90 is 28 years. If 100 g of strontium-90 is currently in a sample of soil, how much will be in the soil in 65 years?

SC 3. Tritium (hydrogen-3), a by-product of the CANDU nuclear power reactor, has a half-life of 12.3 years. How much time is required for its radioactivity to reach 1/4 its original level?

Check your work with the answer in the appendix.

Watch and Listen

Go to the Physics 30 Multimedia DVD and explore half-lives using the "Half-life Tutorial."

Self-Check

You may check your understanding of half-lives by completing the assessment questions in the "Half-life Simulation."

SC 4. A student studying radioactivity makes the following measurements from a radioactive sample.

Time (s)	Decays (Bq)
0.0	100.00
1.0	75.79
2.0	57.43
3.0	43.53
4.0	32.99
5.0	25.00
6.0	18.95
7.0	14.36
8.0	10.88
9.0	8.25
10.0	6.25
11.0	4.74
12.0	3.59

    a. What is the independent variable?

    b. What is the dependent variable?

    c. Graph the information.

    d. What type of relationship is shown on the graph?

    e. From your graph what is the half life of the sample?

    f. After how many seconds will there be less than 1.0 Bq?

    g. Will the decays ever reach zero?

Check your work with the answer in the appendix.

Reflect and Connect

In order to verify the accuracy of radioactive dating it must be tested using samples of known age. For example, could radioactive dating confirm the age of a piece of wood from a mummiform coffin from Egypt dated, on stylistic grounds, to be from the Ptolemaic period, 332 B.C.? Could it accurately predict the age of acacia wood from the tomb of Zozer at Sakkara, which is known to be 4650 ±75 years old?

In all such tests, observations matched predictions, verifying the accuracy of radiocarbon dating. Once verified, the methodology could be applied to measure the age of any organic sample, such as the Burmis tree in Alberta.

© vnlit/shutterstock

In order to determine the age of a sample using radioactive dating, we will assume that the amount of carbon-14 in the ancient wood, when it died, was identical to the amount of carbon-14 in a similar sample of living wood today. In other words, the amount of carbon-14 in the atmosphere has not changed significantly in the past 5000 years. In reality scientists and archaeologists carefully adjust for variations in atmospheric carbon-14 by comparing values to known values from ice cores, deep-sea sediments, and tree growth rings (dendrochronology).

Module 8: Lesson 2 Assignment

Go to the Module 8 Assignment Booklet and complete RC 1 and RC 2.

Lesson Summary

In this lesson you focused on the following questions:

- What is a half-life?
- How are half-lives used to determine age?

In this lesson you learned that the half-life of a radioactive isotope is defined as the amount of time it takes for half of the radioactive nuclei to decay. Graphing the amount of parent nuclei versus time gives the following mathematical expression for the number of original parent nuclei in a radioactive sample after a given time interval.
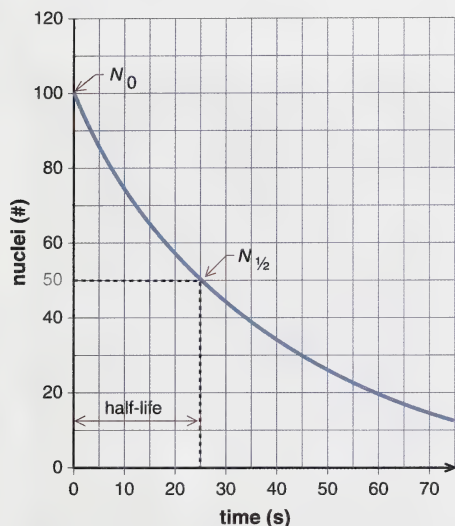
$$N = N_0 \left(\frac{1}{2}\right)^n$$

Both the graphical representation and the mathematical expression can be used to determine the age of a radioactive sample. Radioactive dating is based on comparing the remaining amount of parent nuclei to the amount that was originally in the sample. Using this and the known half-life of the material, it is possible to accurately determine its age.

Lesson Glossary

activity or decay rate: the number of nuclei in a sample that decays in a given time interval

becquerel (Bq): the unit of radioactivity equal to one decay per second

half-life: the time it takes for half the radioactive nuclei in a sample to decay

Lesson 3—Fission and Fusion

Get Focused

In the Big Picture at the beginning of the module molecules, atoms, protons, and particles were characterized as different sized balls. The Sun is powered by two very small balls colliding to produce a slightly larger ball and release a huge amount of energy. In the case of fusion, multiple hydrogen nuclei join together to form a heavier helium nucleus, accompanied by the release of massive amounts of energy. It would be an ideal source of power if it could be sustained in a reactor on Earth, such as the one seen in the photograph. Such a reactor would combine multiple hydrogen nuclei to form helium, which is environmentally clean and biologically harmless.
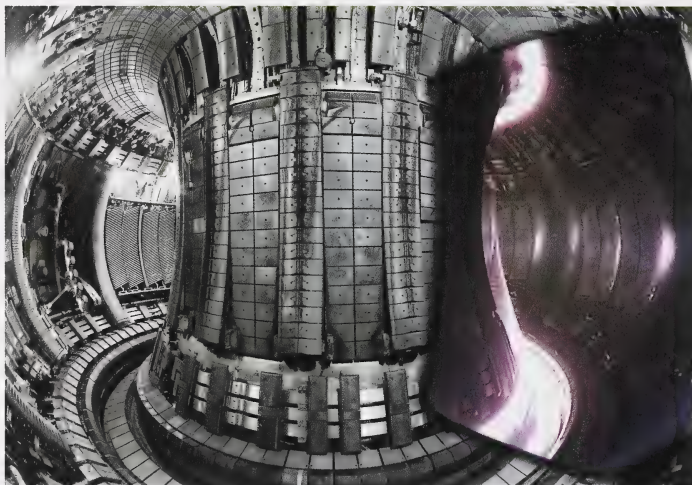
© EFDA-JET; Photo: cp05j-438-01
Split image showing the interior of a nuclear fusion reactor and the superheated plasma when it is in operation.

However, fusion reactions involving hydrogen need to have sustained temperatures ranging from 45–400 million degrees Kelvin. In the Tokamak reactor vessel, plasma is heated in a doughnut-shaped vessel called a torus. Magnetic fields are used to contain the superheated plasma, preventing it from contacting the vessel walls.

plasma: ionized gas in which the electrons have been separated from the nucleus

Although very promising in theory, current fusion technology can only sustain the reaction for a few seconds while producing only slightly more energy than it consumes. Significant technological advances need to be made before fusion becomes a practical energy source, one that is clean, safe, and abundant.

Watch and Listen

Go to the Physics 30 Multimedia DVD and watch the video "Joint European Tours Nuclear Fusion Research Facility" ("The Starmakers") to see the latest reactor technology in action.

In Lesson 3 you will compare and contrast the characteristics of fission and fusion reaction.

In this lesson you will focus on answering the following essential questions:

- Why do nuclear reactions release so much energy?
- What is nuclear fission?
- What is nuclear fusion?

Module 8: Lesson 3 Assignment

Your teacher-marked Module 8: Lesson 3 Assignment requires you to submit responses to the following:

- Lab—LAB 1, LAB 2, LAB 3, LAB 4, and LAB 5
- Reflect and Connect—RC 1

The other questions in this lesson are not marked by the teacher; however, you should still answer these questions. The Self-Check and Try This questions are placed in this lesson to help you review important information and build key concepts that may be applied in future lessons.

After a discussion with your teacher, you must decide what to do with the questions that are not part of your assignment. For example, you may decide to submit to your teacher the responses to Try This questions that are not marked. You should record the answers to all questions in this lesson and place those answers in your course folder.

Explore

The Energy of Nuclear Reactions

Photo courtesy of National Nuclear Security Administration / Nevada Site Office
The first atomic artillery shell fired from a 280-mm artillery gun, May 25, 1953, Nevada Proving Grounds, USA.

Nuclear reactions involve vast amounts of energy, either creating massive fireballs in a chain reaction or slowly releasing significant amounts of energy over many years in a nuclear reactor. Recall from Module 8: Lesson 1 that particles (nucleons) make up a nucleus that is held together by a strong nuclear force. Both nuclear fission and fusion reactions change the number of nucleon particles, so work must be done against the strong nuclear force during any nuclear reaction.

The amount of work required to separate all the nucleons in a given atom is referred to as the **binding energy**. It is equal to the difference between the energy of all the nucleons when they are free compared to when they are contained in the nucleus.

binding energy: the net energy required to liberate all of the protons and neutrons in a nucleus (overcome the strong nuclear force)

$$E_{\text{binding}} = E_{\text{nucleons}} - E_{\text{nucleus}}$$

Dividing the binding energy of the nucleus by the number of nucleons making it up gives a value for the binding energy of each nucleon.

$$E_{\text{per nucleon}} = \frac{E_{\text{binding}}}{A}$$

A — the atomic mass number

Stable nuclei have greater binding energy per nucleon than unstable nuclei. Nuclei with atomic masses in the range of 58–62 (iron-nickel) are the most stable, with the highest binding energy per nucleon. Smaller atoms, such as hydrogen-2, have a very small amount of binding energy per nucleon, making them less stable. At the same time much larger atoms, such as uranium-238 also have a reduced binding energy per nucleon making it unstable. In order to become more stable, very small nuclei can become larger by combining in the process of fusion, and very large nuclei can become smaller by breaking down into smaller nuclei in the process of fission. The result in either process is to move toward a medium-sized stable nucleus with the greatest amount of binding energy per nucleon.

For both **fission** and **fusion** reactions, the energy released is equal to the difference between the total binding energy of the original nucleus or nuclei and the final binding energy of the nucleus or nuclei.

fission: reaction in which a nucleus with more than 120 nucleons splits into smaller nuclei with greater binding energy per nucleon

fusion: reaction in which a nucleus with fewer than 60 nucleons combines with another to form a larger nucleus with greater binding energy per nucleon

$$\Delta E = E_{\text{binding final}} - E_{\text{binding initial}}$$
$$\Delta E = E_{\text{bf}} - E_{\text{bi}}$$

For both fission and fusion, the binding energy of the final (resulting) atom(s) is much larger than the binding energy of the initial atom(s), leading to both a more stable nucleus and the release of a large amount of energy.

The change in binding energy also corresponds exactly to the change in mass between the original and new nuclei, according to Einstein's mass-energy equivalency ($E = mc^2$). In this respect, the energy released in a nuclear reaction is based on the change in mass before and after the reaction.

$$\Delta E = \left(m_{\text{f}} - m_{\text{i}} \right) c^2$$

According to this equation, even a very small change in mass multiplied by the square of the speed of light (9×10^{16}) will result in a large release of energy.

Nuclear Fission
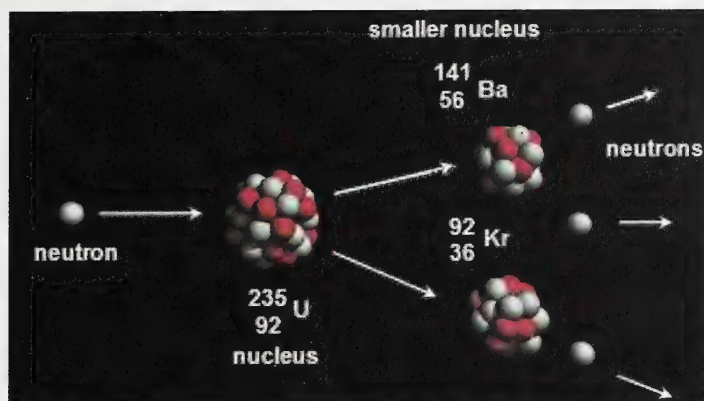
The Canadian CANDU nuclear reactor uses the fission of uranium-235 as an energy source. In this reactor a free neutron is absorbed by a uranium nucleus causing it to become unstable and break apart into two smaller nuclei accompanied by the release of several more neutrons.

If the free neutrons encounter more uranium atoms they will be absorbed again, causing further fission and the production of more neutrons capable of continuing the process. If enough uranium is present in a small enough area (critical mass), the probability of a neutron causing another uranium atom to split is very high and a chain reaction will occur. This would cause the release of a massive amount of energy in a very short period of time, producing a nuclear explosion. In a nuclear reactor, by contrast, the uranium atoms are spread out in fuel rods and some of the released neutrons are blocked by control rods in order to slow down the chain reaction. When the reaction rate is slow, a smaller amount of energy is released over a long period. In essence, a nuclear reactor is a nuclear bomb going off in a controlled manner over a prolonged period. When all or most of the uranium-235 atoms in the fuel have been spent, the reactor cools, at which point new fuel would have to be inserted to ensure continued energy production.

Example Problem 1. How much energy is released by the fission of one U-235 atom?

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$
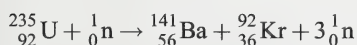
Given

The atomic masses come from "Table 7.5" and "7.6" on page 881 of your physics textbook.

$m_u = 235.043\,930$ u
$m_n = 1.008\,665$ u
$m_{Ba} = 140.914\,412$ u
$m_{Kr} = 91.926\,156$ u

Required

the amount of energy released

Analysis and Solution

Determine the mass defect.

$$\Delta m = m_{final} - m_{initial}$$
$$= (m_{Ba} + m_{Kr} + 3m_n) - (m_u + m_n)$$
$$= (140.914\,412\text{ u} + 91.926\,156\text{ u} + 3 \times 1.008\,665\text{ u}) - (235.043\,930\text{ u} + 1.008\,665\text{ u})$$
$$= 0.186\,032\text{ u}$$

Change the mass defect into kilograms.

$$\Delta m = (0.186\,032\text{ u})\frac{(1.66 \times 10^{-27}\text{ kg})}{(1\text{ u})}$$
$$= 3.0881312 \times 10^{-28}\text{ kg}$$

Determine the amount of energy released.

$$E = mc^2$$
$$= (3.088\,131\,2 \times 10^{-28}\text{ kg})(3.00 \times 10^8\text{ m/s})^2$$
$$= 2.779\,318\,08 \times 10^{-11}\text{ kg}$$

Paraphrase

The energy released by the fission of one uranium-235 atom is 2.78×10^{-11} J.

This value may seem small by comparison, but in a single kilogram of uranium there are enough fissionable uranium atoms to produce 7.09×10^{13} J of nuclear energy, which is approximately 1.6 million times greater than the chemical energy within one kilogram (≈1.4 litres) of gasoline.

 Read

Read "Comparing Chemical Energy with Nuclear Energy" on page 820 of the textbook.

Watch and Listen

When dealing with nuclear reactors the rate of the reaction must be controlled to prevent a chain reaction. In the fission of uranium, each uranium nucleus decays spontaneously, which is a very slow reaction. This decay also occurs when a uranium nucleus absorbs a neutron in a nuclear reactor, which can be slow or fast depending on the position of the control rods. It is slowed down when the ejected neutrons are absorbed by inserting control rods, or it is sped up by removing the control rods, which lets the ejected neutrons strike other uranium nuclei, thus continuing the chain reaction. In the following animation you will see how a chain reaction spreads exponentially.

Three animationss are available to explain nuclear reactions. Do an Internet search using the term "atomic archive." This should take you to a website that explores the histrory, science, and more of the invention of the atomic bomb. When you get to the website, use the website's search function to locate "Nuclear Chain Reaction Animation." This animation will show how, in a nuclear bomb, the chain reaction is engineered to occur as rapidly as possible to produce the largest explosion possible.

Next, find "Nuclear Fission Animation." This animation shows the reactants and products of a uranium-based nuclear fission reaction, like the one that powers nuclear power reactors.

Finally, find "Nuclear Fusion Animation." Fusion reactions release much more energy than fission reactions; however, this is also what makes them hard to control. This animation shows the reactants and products of a deuterium (H-2) and tritium (H-3) fusion, which produces a helium nucleus and a neutron. This is the main form of fusion that powers Earth's Sun.

If you're having trouble finding any of the animations, click on "Media" in the top navigation bar on the website, and then on "Animations" on the page that appears.

Try This

TR 1. Complete "Practice Problems" 1 to 3 on page 819 of the textbook.

Nuclear Fusion

Nuclear fusion is similar to nuclear fission in that the binding energy of the products is much higher than the starting nuclei. The process to achieve this, however, is based on combining nuclei rather than breaking them down. At temperatures greater than 100 million Kelvin, the small nuclei of tritium and deuterium will combine to form larger, more stable helium atoms while releasing an amount of energy proportional to the change in mass (mass defect) or equal to the difference in binding energies before and after the reaction.

$$^3_1\text{H} + {}^2_1\text{H} \rightarrow {}^4_2\text{He} + {}^1_0 n$$
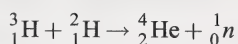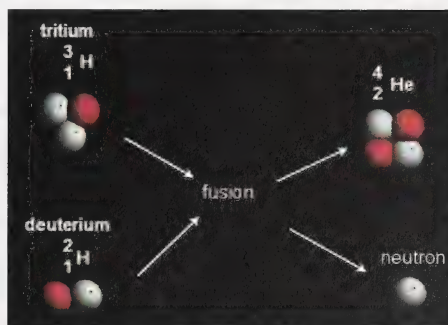
Nuclear fusion powers the Sun, which has enough hydrogen to maintain its present rate of energy production for another 6 billion years. On Earth, hydrogen is abundant in the water, which, in theory, could provide a seemingly infinite supply of clean, safe nuclear energy.

Watch and Listen

Go to the Physics 30 Multimedia DVD and watch the video "Sun Flares," which is about solar flares. The video demonstrates the energy released by the nuclear fusion on the surface of the Sun. When the Sun's magnetic field fluctuates it allows massive amounts of plasma to arc off into space. The arcs are often larger in diameter than Earth.

Commercial fusion reactors could provide phenomenal amounts of non-polluting electrical energy. The EFDA (European Fusion Development Agreement) sponsors JET (Joint European Torus), a commercial fusion reactor development site. EFDA scientists are researching how to safely recreate the reaction that powers the Sun to produce electricity on Earth. They used the information gathered from the JET project to design a large reactor called ITER, which is scheduled to begin operation in 2016. It will be the biggest fusion furnace ever built, twice as large as any previously built, and will produce plasma at temperatures of hundreds of millions of degrees Celsius. Go to the Physics 30 Multimedia DVD and watch the video "Inside a Reactor," which shows the inside of the JET reactor during a plasma experiment.

Read

Read "Fusion" on pages 821 to 823 of your physics textbook. Page 821 provides more extensive detail on the reactions occurring on the Sun and includes references to the products released (neutrinos, positrons or antielectrons, and gamma rays).

Try This

TR 2. Read "Example 16.16" and complete "Practice Problem" 1 on page 822 of the textbook.

How does a nuclear fission reactor work? Why are they so dangerous if they get out of control? What caused the Chernobyl nuclear accident? Go to the Physics 30 Multimedia DVD and open the "Nuclear Reactor Simulation," take your operator test and see if you can run the reactor efficiently. You can also discover how you could accidentally cause an explosion. (Be sure to open the "Information" tab in the simulation.)

After completing the nuclear reactor simulation, post your response to the following Lab questions in the discussion area of your class. You may need to return to the simulation.
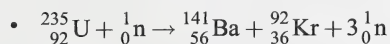
Module 8: Lesson 3 Assignment

Go to the Module 8 Assignment Booklet and complete LAB 1, LAB 2, LAB 3, LAB 4, and LAB 5.
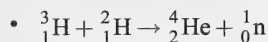
⚠ Reflect and Connect

Nuclear energy comes in one of two varieties:

1. fission of large nuclei like uranium-235

   - $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$

2. fusion of small nuclei like tritium and deuterium

   - $^{3}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$

The fission of uranium-235 is widely used in reactors, such as the CANDU reactor. Fusion does not produce the unstable and biologically dangerous daughter nuclei of fission. Fusion produces stable helium atoms. Research is being conducted to find a technological solution to sustain the fusion reaction. However, a sustained and practical use of fusion is yet to be achieved, but it holds great promise as an infinite source of clean, environmentally safe energy.
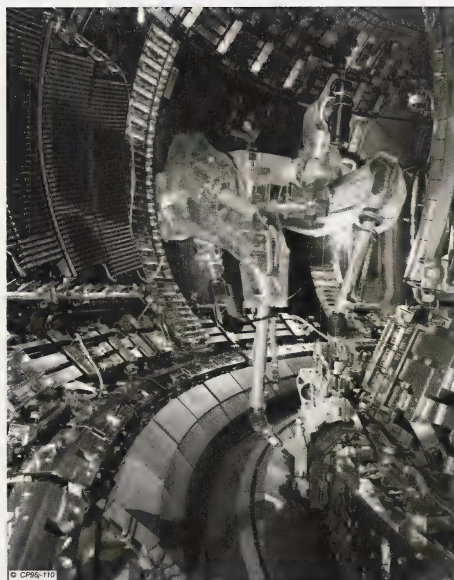
© EFDA-JET; Photo: CP96j-110

? Module 8: Lesson 3 Assignment

Go to the Module 8 Assignment Booklet and complete RC 1.

Lesson Summary

In this lesson you focused on the following questions:

- Why do nuclear reactions release so much energy?
- What is nuclear fission?
- What is nuclear fusion?

In this lesson you learned that both fission and fusion nuclear reactions are processes that lead to an increase in the binding energy per nucleon, increasing the stability of the resulting nuclei. In the process of fission, a nucleus with more than 120 nucleons splits into smaller nuclei with greater binding energy per nucleon. In the process of fusion, a nucleus with fewer than 60 nucleons combines with another to form a larger nucleus with greater binding energy per nucleon. Both of these nuclear reactions release large amounts of energy.

For both fission and fusion reactions, the energy released is equal to the difference between the total binding energy of the original nucleus or nuclei and the final binding energy of the nucleus or nuclei. The energy released can also be found by calculating the total mass defect during the reaction. This mass defect was transformed into energy according to Einstein's mass-energy equation $E = mc^2$.

The product of fusion (helium) is stable and safe, which is in contrast to the unstable, dangerous daughter nuclei produced in a fission reaction.

In fission, a free neutron is absorbed by a large nucleus, such as uranium-235, causing it to become unstable and break apart into two smaller nuclei, accompanied by the release of several more neutrons. If the free neutrons encounter more uranium atoms they will again be absorbed, causing further fission and the production of more neutrons capable of continuing the process. Left unchecked with sufficient amounts of uranium, this chain reaction could produce a nuclear explosion. Controlling the rate of the chain reaction allows the energy to be released slowly, a strategy employed by current fission reactors.

In fusion, temperatures greater than 100 million Kelvin are needed to cause small nuclei, such as tritium and deuterium, to combine and form larger, more stable helium atoms while releasing an amount of energy equal to the change in the mass or difference in binding energies before and after the reaction. Advancing fusion reactor technology holds the promise of a seemingly infinite supply of clean energy.

Lesson Glossary

binding energy: the net energy required to liberate all of the protons and neutrons in a nucleus (overcome the strong nuclear force)

fission: when a nucleus with more than 120 nucleons splits into smaller nuclei with greater binding energy per nucleon

fusion: when a nucleus with fewer than 60 nucleons combines with another to form a larger nucleus with greater binding energy per nucleon

plasma: ionized gas in which the electrons have been separated from the nucleus

Module 8—Nuclear Decay, Energy, and the Standard Model of the Atom

Lesson 4—The Subatomic World

▼ Get Focused

Sometimes you have to think big to find something really small. Deep underground, underlying the border between Switzerland and France, is a gigantic scientific instrument. The Large Hadron Collider (LHC) is the biggest machine in the world. It is nearly 27 km in circumference and contains 9300 magnets along a circular path. When it operates at full power, trillions of protons travel its circumference 11 245 times every second—nearly the speed of light!
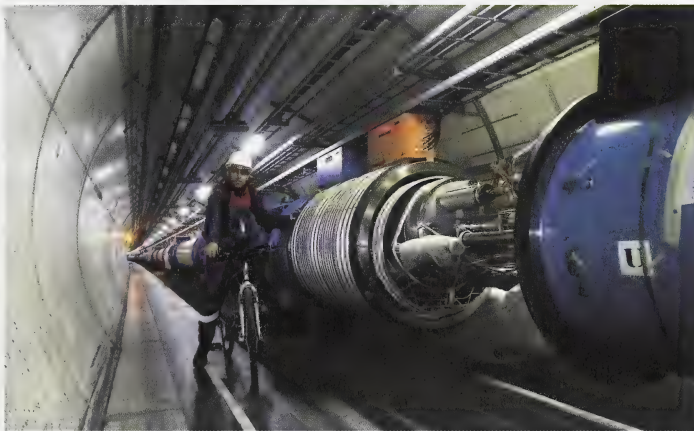
© CERN 2008. Used with permission.
The Large Hadron Collider is the world's most powerful machine. It is 27 km long and is buried 100 m below the border of Switzerland and France.

Coming in the opposite direction and at the same speed, a second group of protons collide with them. All told, 600 million collisions should occur every second, with energies that will produce temperatures 100 000 times that of the Sun's core. If it sounds impressive, that's because it is! With these energies, never before seen on Earth, the protons will break apart, revealing the subatomic world that makes them up. The products of such a high-energy collision should help scientists answer some unresolved questions about the subatomic world, such as the following:

- What is the origin of mass? What makes up the mass in a nucleon?
- What makes up 96% of the universe? What is dark matter?
- Where is antimatter, as predicted by the standard model of the atom?
- What happened in the first few seconds of the universe?
- Are there other dimensions in the space-time continuum?

These are big, heavy questions. They will require massive amounts of energy to study. The LHC was built to provide enough energy to try to answer questions like these and to fill in the knowledge gaps that still exist in our understanding of the universe beyond our planet and reveal the fundamental make-up of the subatomic universe. These questions are beyond the scope of this course but show that, despite claims that humans understand the universe, there are still many basic concepts that we cannot explain.

Watch and Listen

Go to the Physics 30 Multimedia DVD and take a look at how the LHC will use hydrogen gas to investigate the quarks and particles from the inside of a proton in the video called "The Bottle to Bang."

In Lesson 4 you will learn about ongoing developments that are informing our models of the structure of matter.

In this lesson you will focus on answering the following essential questions:

- How is it possible to probe the subatomic world?

- What subatomic particles make up the proton and neutron?

- How does the discovery of antimatter and subatomic particles inform the latest models concerning the structure of matter?

Module 8: Lesson 4 Assignment

Your teacher-marked Module 8: Lesson 4 Assignment requires you to submit responses to the following:

- Assignment—A 1, A 2, A 3, A 4, and A 5
- Reflect and Connect—RC 1, RC 2, RC 3, and RC 4

After a discussion with your teacher, you must decide what to do with the questions that are not part of your assignment. For example, you may decide to submit to your teacher the responses to Try This questions that are not marked. You should record the answers to all questions in this lesson and place those answers in your course folder.

Explore

Probing the Subatomic World

When two particles such as protons collide at sufficient energy, they break down into smaller particles, which leave behind tracks as they move away from the collision. The illustration here shows the particle tracks that could occur when two particles collide. These tracks are used to deduce the nature of the subatomic particle that created them.
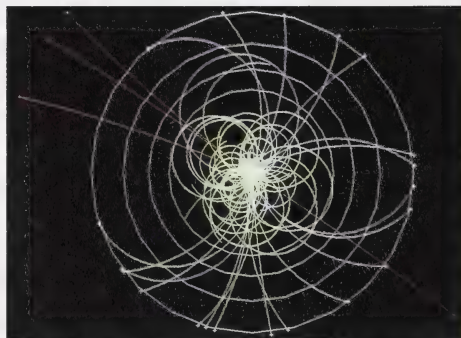
© CERN 2008. Used with permission.

For example, if the collision occurs in a uniform magnetic field, the direction of the curved tracks reveals the charge of the particle. The radius of curvature can also be measured to give the charge-to-mass ratio of the particle in a way similar to that of a mass spectrometer.

Early devices designed to capture particle tracks include the **cloud chamber** and **bubble chamber**.

Cloud Chamber	Bubble Chamber
A device that contains dust-free supersaturated water or ethanol vapour, which will condense along the path of a particle that moves through it.	A device that contains liquefied gas, such as hydrogen, which boils and forms bubbles along the path of a particle that moves through it.

Only charged particles and photons capable of ionizing the material in the chambers will produce tracks. The nature of the charge can be determined with the appropriate hand rule and the charge-to-mass ratio can be calculated based on the radius of the curvature using $\frac{q}{m} = \frac{v}{Br}$. To review charge-to-mass ratio, see Module 7: Lesson 1 about cathode rays and Thomson's experiment.

bubble chamber: a device that tracks particles using bubbles in liquefied gas

cloud chamber: a device that tracks particles using condensed gas vapours

Read

Read "Detecting and Measuring Subatomic Particles" on pages 830 to 835 of your physics textbook.

Try This

TR 1. Complete "Practice Problems" 1 and 2 on page 834 and "Check and Reflect" questions 2 and 5 on page 835 of the textbook.

Module 8: Lesson 4 Assignment

Go to the Module 8 Assignment Booket and complete A1.

The amount of energy required to overcome the strong nuclear force and scatter the contents of the nucleus is significant. Consider the energy used in various experiments so far:

- 13.6 eV: ionizes the hydrogen atom in the study of electron energy levels

- 1.0×10^7 eV: produces Rutherford scattering, revealing the nature of the nucleus

Early particle accelerators were sometimes called atom smashers, since they could develop enough energy to scatter the contents of the nucleus. The strong nuclear force can be overcome in a particle accelerator, causing the contents of a nucleon to scatter.

- 2.0×10^9 eV: produces heavier nuclei and scatters nuclear particles in a collision

Current particle accelerators, such as the Large Hadron Collider, can generate more energy than that needed to overcome the strong nuclear force.

- 1.4×10^{13} eV: maximum energy used in the LHC to expose subatomic particles

Read

Read "Probing the Structure of Matter" on pages 840 and 841 of the textbook.

Fundamental Particles

Antimatter

Prior to the development of quantum theory it was believed that all matter was made of three fundamental particles: electron, proton, and neutron. More recent developments in this theory predict the existence of other subatomic particles, some with very peculiar properties. For example, quantum theory predicts that every kind of particle has a corresponding antiparticle. The antiparticle of an electron is called the positron, which has an identical magnitude charge-to-mass ratio as an electron but with a positive charge. American physicist Carl Anderson identified it in particle tracks in 1932.

antimatter: an extension of the concept of normal matter that is made up of particles where antimatter is made up of antiparticles

All particles have an antiparticle.

When a particle and its antiparticle collide, they are both annihilated and produce a pair of high-energy gamma ray photons. The collision of an electron and a positron are part of the nuclear process in stars. This matter-antimatter collision can be described with an equation $e^+ + e^- \rightarrow 2\gamma$.

Example Question 1. How much energy is released when an electron-positron pair annihilate?

Given

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

Required

the energy released from the annihilation

Analysis and Solution

Remember that in the annihilation one electron and one positron's worth of mass is annihilated.

$$E = mc^2$$
$$= 2\left(9.11 \times 10^{-31} \text{ kg}\right)\left(3.00 \times 10^8 \text{ m/s}\right)^2$$
$$= 1.6398 \times 10^{-13} \text{ J}$$

Paraphrase

One electron positron pair annihilation releases 1.64×10^{-13} J.

Example Question 2. How much energy would be released from the annihilation of 1.00 kg of electrons in an antimatter reaction?

Given

$$\text{mass} = 1.00 \text{ kg}$$
$$m_e = 9.11 \times 10^{-31} \text{kg}$$

Required

the energy released from the annihilation of 1.00 kg of electrons

Analysis and Solution

Determine the amount of energy released; remember that to annihilate 1.00 kg of electrons takes 1.00 kg of positrons.

$$E = mc^2$$
$$= 2\left(1.00 \text{ kg}\right)\left(3.00 \times 10^8 \text{ m/s}\right)^2$$
$$= 1.80 \times 10^{17} \text{ J}$$

Paraphrase

When 1.00 kg of electrons is annihilated it will produce 1.80×10^{17} J of energy.

Remember from page 820 in your physics textbook that 1.0 kg of uranium releases 7.10×10^{13} J/kg and that 1.0 kg of gasoline releases 4.4×10^7 J/kg. So, antimatter reactions are extremely energy dense.

⚠️ Module 8: Lesson 4 Assignment

Go to the Module 8 Assignment Booklet and complete A 2 and A 3.

Mediating Particles

Quantum theory also predicts the existence of particles that produce fundamental forces like gravity and the strong nuclear force. These **mediating particles** are thought to

mediating particle: a virtual particle that carries a fundamental force

carry the fundamental forces and exist for such a short time that they are undetectable. The following table summarizes the mediating particles and their relationship to the fundamental forces.

Mediating Particle	Fundamental Forces	Particles Observed?
photons	electromagnetic	yes
gluons	strong nuclear	indirectly
gravitrons	gravitational	no
W^+, W^-, Z^o	weak nuclear	yes

🔺 Read

Read "Quantum Theory and the Discovery of New Particles" on pages 836 to 838 of your textbook.

The Subatomic Zoo
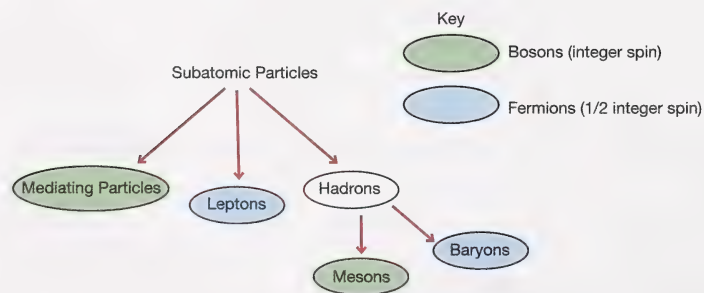
More than 300 more subatomic particles have been discovered using new and more powerful particle accelerators and detectors. These particles have been classified by family.

Leptons do not interact via the strong nuclear force and are relatively small.

Hadrons do interact via the strong nuclear force and are subdivided based on size (*meso* is Greek for "middle"; *barus* is Greek for "heavy"). The particles are also classified by "spin," which is analogous to describing the rotational momentum of the spinning particle. Boson and fermion are classifications based on the spin of the particle.

🔺 Read

Read "The Subatomic Zoo" on pages 842 to 844 of your physics textbook. Take note of "Table 17.3: An Introduction to the Subatomic Zoo," which identifies the particles, symbols, mass, and lifetime of many subatomic particles.

🔺 Try This

TR 2. Complete "Check and Reflect" questions 1 to 5 on page 844 of the textbook.

Quarks and Decay

Given the large number of subatomic particles that were discovered using collisions and particle accelerators, it wasn't long before scientists suggested that a large number of these particles were, in turn, built from just three smaller particles called **quarks**. The first quark is called an "up" quark and has a charge of $+\frac{2}{3}$ e. The second quark is called a "down" quark and has a charge of $-\frac{1}{3}$ e. The third particle is called the "strange" quark and has a charge of $-\frac{1}{3}$ e. Using the powerful Stanford Linear Accelerator, scientists discovered that the mass and charge of a proton are indeed concentrated in three regions within the particle, supporting the quark model.

Protons and neutrons are each composed of three quarks.

> **quark:** a fundamental particle in the hadron family

Proton

up — $+\frac{2}{3}$ e up — $+\frac{2}{3}$ e

down — $-\frac{1}{3}$ e

$$\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$$

Neutron

up — $+\frac{2}{3}$ e down — $-\frac{1}{3}$ e

down — $-\frac{1}{3}$ e

$$\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$$
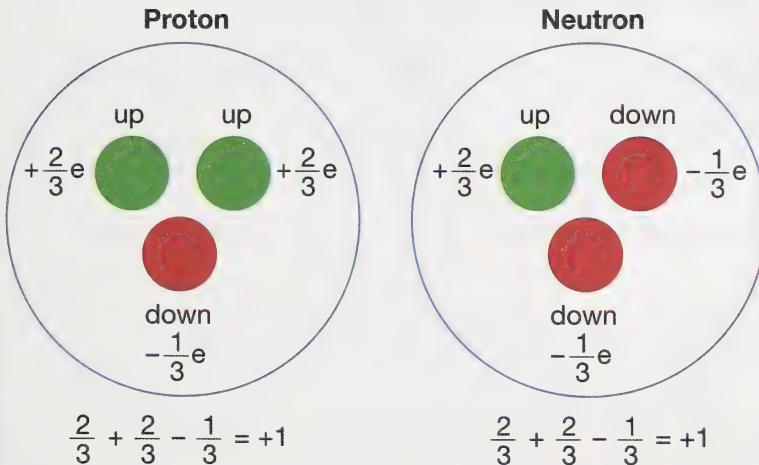
The up, down, and strange quarks are first-generation quarks. Subsequent research and theory has identified three other quarks named charm, beauty, and truth.

 Read

"Table 17.5: Some Properties of Quarks" on page 846 of the textbook summarizes the first-, second-, and third-generation quarks.

The quark model and weak electric force help explain nuclear changes, like beta and beta-positive decay. For example, during the decay process a down quark can change into an up quark, leading to the emission of an electron and an electron antineutrino. The following are both the equation and graphical representation of this process showing the conservation of mass and charge.
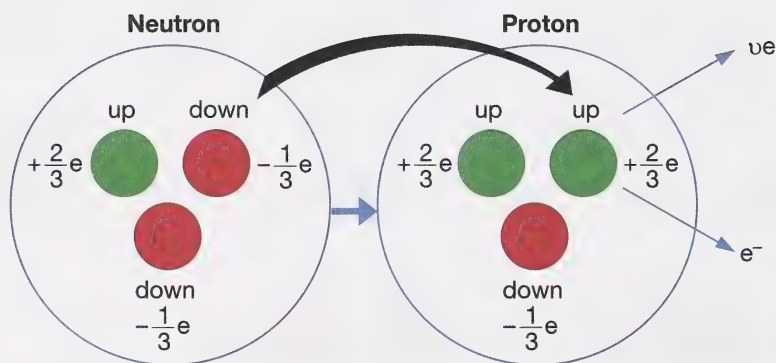
Beta Decay

word equation :   neutron → proton + electron + electron antineutrino

symbol equation : $udd \rightarrow uud + e^- + \bar{v}_e$

charge conservation : $\left(+\dfrac{2}{3} - \dfrac{1}{3} - \dfrac{1}{3}\right) \rightarrow \left(+\dfrac{2}{3} + \dfrac{2}{3} - \dfrac{1}{3}\right) + (-1)$

$$0 \rightarrow +1 - 1$$
$$0 \rightarrow 0$$

Beta Positive Decay

word equation : proton → neutron + positron + neutrino

symbol equation : uud → udd + e^+ + ν_e

charge conservation : $\left(+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}\right) \rightarrow \left(+\frac{2}{3}-\frac{1}{3}-\frac{1}{3}\right)+(1)$

$$1 \rightarrow 0+1$$

$$1 \rightarrow 1$$
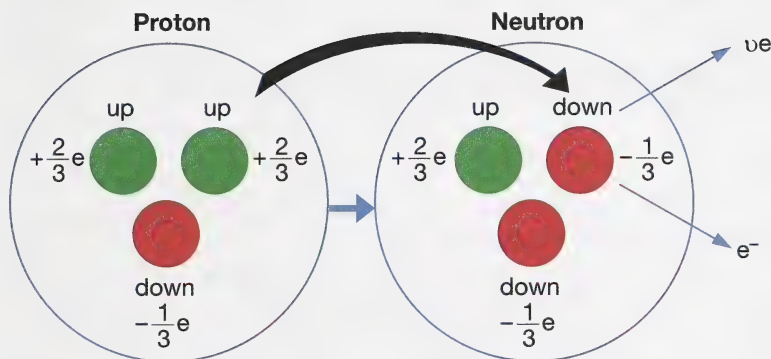
？ Module 8: Lesson 4 Assignment

Go to the Module 8 Assignment Booklet and complete A4 and A5.

The Standard Model

The standard model summarizes the most current understanding of the atom with the following key concepts:

standard model: the current theory describing the nature of matter and the fundamental forces

- All matter is composed of 12 fundamental particles and their respective anti-particles (six quarks and six leptons).

- The electromagnetic force and the weak nuclear force are both aspects of the same fundamental force (electroweak force), supplied by the W+, W−, Zo mediating particles that have been observed.

- All of the quarks have a quantum property called "colour," which is not related to visible colour, but is used to describe the strong nuclear force. This theory is referred to as quantum chromodynamics.

Even though the standard model explains three of the fundamental forces, it cannot explain how gravity works. At the extremely small scale of the atom, gravity is so weak as to be nonexistent and, therefore, does not affect subatomic actions. However, one of the goals of physicists is to develop a single theory and set of equations that describe everything in the universe, optimistically called the grand unified theory or the theory of everything.

Current theoretical research is moving toward a grand unified theory that could connect the electroweak force with chromodynamics and gravity. At the same time, research continues into string theory, which may connect gravity with the other three fundamental forces. In this theory the particles are treated as tiny vibrating strings of mass-energy that are quantized similarly to standing waves. At the moment these are just theories waiting to be tested, refined, rejected, and revised in a similar way to the thousands of ideas and theories that have come before them. In many respects, the inside of the atom remains undiscovered territory. Like the furthest reaches of deep space, it can only be explored with powerful and continually evolving human technology and ingenuity.

Read

Read "Quarks and the Standard Model" on pages 845 to 849 of your textbook.

Self-Check

SC1. What are the 12 particles of the standard model?

SC 2. Rank the four natural forces from weakest to strongest.

Check your work with the answers in the appendix.

Reflect and Connect

This pixel detector on the Large Hadron Collider will track the particles emitted by the collision of protons when each proton is travelling at nearly the speed of light in opposite directions. The particle emitted in these high-energy collisions reveals the internal workings of the atom. Powerful technology is required to look deep inside the subatomic world, just as powerful technology is required to look deep into the universe.

© CERN 2008. Used with permission.
The silicon pixel detector attached to the LHC.

The atom is as tiny as the universe is massive, so it is no wonder that vast amounts of energy and technology are required to refine the theories and ideas that describe them both! On these scales, new terminology and ideas can become so complex that it is easy to overlook all of the connections.

Read

© CERN 2008. Used with permission.
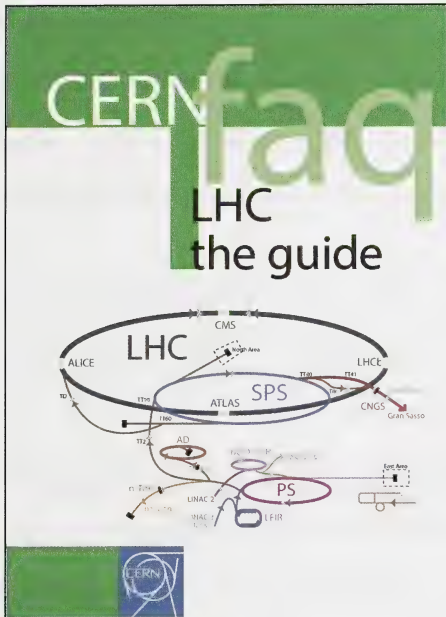
Go to the Physics 30 Multimedia DVD and read "CERN's FAQ Booklet" of the design, function, and power of the Large Hadron Collider as it relates to everything we know so far about the atom.

All of the ideas, current understanding, and technology required to investigate further are explained in this text. There are some very amazing facts on the LHC machine as well.

Reflect and Connect

Before completing the Assignment, go to the Module 8 Assignment Booklet and read the Reflect and Connect questions; then go to the Physics 30 Multimedia DVD and watch the "CERN Development Video," which goes over the development of CERN over the past 50 years. Don't complete the questions until you have watched the video.

Module 8: Lesson 4 Assignment

Go to the Module 8 Assignment Booklet and complete RC 1, RC 2, RC 3, and RC 4.

RC 1. Name two famous physicists shown in the video and state why they are famous as physicists.

RC 2. What are two physics discoveries that have been made at CERN in the past 50 years?

RC 3. Why is CERN (the European Organization for Nuclear Research) significant for scientists worldwide and what does it show about cooperation in the scientific community?

RC 4. State two ways that the application of the work at CERN has changed life for everyday people.

Lesson Summary

- How is it possible to probe the subatomic world?

- What subatomic particles make up the proton and neutron?

- How does the discovery of antimatter and subatomic particles inform the latest models concerning the structure of matter?

In this lesson you learned that particle tracks can be interpreted to identify the charge-to-mass ratio and type of charge on subatomic particles. By colliding particles, such as protons, at extremely high energies, the contents of these particles can be probed and studied. Current particle accelerators are among the most powerful machines ever built and are capable of causing particle collisions at energies never before seen on Earth.

Based on particle track research and theory, the subatomic world is composed of strange ideas and particles such as antimatter, mediating particles, and the quarks that make up protons and neutrons. Some evidence for up and down quarks is provided by beta decay and beta-positive decay, which is caused by the electroweak force.

Beta Decay

neutron $\rightarrow$ proton + electron + electron antineutrino

$$\text{udd} \rightarrow \text{uud} + e^- + \bar{v}_e$$

Beta Positive Decay

proton $\rightarrow$ neutron + positron + neutrino

$$\text{uud} \rightarrow \text{udd} + e^+ + v_e$$

Current theory that relates the mediating particles to the fundamental forces of electroweak and strong nuclear force are contained in the Standard Model, which is evolving as more experimental evidence gathers. In subatomic research, theory and observation interact, one leading to the other and vice versa. Together, both theoretical and experimental physicists are working toward a grand unified theory, or theory of everything, that will bring connection to all the fundamental forces of the universe and the particles that mediate, create, and sustain them.

Lesson Glossary

antimatter: an extension of the concept of normal matter that is made up of particles where antimatter is made up of antiparticles

All particles have an antiparticle.

bubble chamber: a device that tracks particles using bubbles in liquefied gas

CERN: Conseil Européen pour la Recherche Nucléaire (world's largest particle physics laboratory)

CERN had the first web server and posted the first page on the World Wide Web. See CERN's website to see that historic first page.

cloud chamber: a device that tracks particles using condensed gas vapours

fundamental particle: a particle that cannot be divided into smaller particles; an elementary particle

gluon: a mediating particle for the strong nuclear force

graviton: a hypothetical mediating particle for the gravitational force

mediating particle: a virtual particle that carries a fundamental force

quark: a fundamental particle in the hadron family

standard model: the current theory describing the nature of matter and the fundamental forces

virtual particle: a particle that exists for such a short time that it cannot be detected

$$u \rightarrow d + e^+ + \nu_e$$

$$d \rightarrow u + e^- + \bar{\nu}_e$$

Module 8—Nuclear Decay, Energy, and the Standard Model of the Atom

◭ Module Summary

In this module you studied the following questions:

- Which components make up the nucleus of an atom and what keeps them from coming apart?

- What is meant by alpha and beta decay?

- How is the conservation of mass and energy applied to nuclear decay?

- What is a half-life? How does it relate to dating organic and inorganic material?

- Why are nuclear fission and fusion reactions so powerful?

- How is it possible to probe the subatomic world in search of the fundamental particles that make up protons and neutrons?

- Which subatomic particles make up the proton and neutron?

- How do the discovery of antimatter and subatomic particles inform the latest models concerning the structure of matter?

In Lesson 1 you saw that an ionizing smoke detector depends on the unstable americium-241 nucleus in order to detect smoke and save lives. The nucleus is very small but it makes up nearly the entire mass of the atom. It is composed of smaller particles called nucleons: protons and neutrons. With the positively charged protons, Coulomb's law from Module 3: Lesson 2 shows that there is a very strong repulsive electrostatic force between the protons. However, the protons are held in the nucleus by the even stronger nuclear force that holds nucleons together; but it only works over the extremely short distances found in the nucleus of an atom. Most larger nuclei with more than 83 protons are unstable and will decay spontaneously into smaller nuclei. This natural change from one substance to another is called transmutation and it can produce alpha and beta particles.

- Alpha decay $^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$ is characterized by the emission of an alpha particle (helium nucleus) from the nucleus of the parent atom.

- Beta negative decay $^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \bar{\nu}$ is characterized by the emission of a beta negative (electron) and electron antineutrino from the nucleus of the parent atom.

- Beta positive decay $_Z^A X \rightarrow {_{Z-1}^A} Y + {_1^0}\beta + \nu$ is characterized by the emission of a beta positive (positron) and neutrino from the nucleus of the parent atom.

In Lesson 2 you learned that the rate of radioactive decay is described by the half-life of the radioactive isotope. This can be observed and analyzed both graphically, with an exponential regression curve, and mathematically as $N = N_0 \left(\dfrac{1}{2}\right)^n$. Due to the constant decay rate the age of some ancient organic and inorganic substances can be determined by using radioactive dating. Radioactive dating is based on using radioactive isotopes in a sample, such as carbon-14. By comparing the remaining amount of parent nuclei to the amount that was originally in the sample and the known half-life of the isotope, it is possible to determine an age accurately.

In Lesson 3 you examined how nuclear reactions release large amounts of energy by changing mass into energy, called binding energy, using the famous equation, $E = mc^2$. Nuclear reactions occur to increase the binding energy per nucleon and make the nucleus more stable. Small amounts of binding energy are released by alpha and beta decays.

Scientists and engineers are interested in nuclear fission and fusion reactions due to their ability to control the release of huge amounts of binding energy. Nuclear fission is currently used in nuclear power plants. In the process of fission a nucleus with more than 120 nucleons splits into two or more smaller nuclei with greater binding energy per nucleon. Nuclear fusion power is still in its infancy, with a couple of experimental designs being tested. In the process of fusion, a nucleus with fewer than 60 nucleons combines with another to form a larger nucleus with greater binding energy per nucleon. Both reactions, however, have positive and negative aspects.

Lesson 4 showed you that current particle accelerators are some of the most powerful machines ever built, capable of causing particle collisions at energy concentrations never before seen on Earth. Enormous amounts of energy are required to overcome the large binding energy per nucleon caused by the strong nuclear force. Information is gathered in the form of scattering patterns and paths of the emitted particles to find evidence of what happened inside the nuclei of the target atoms.

Based on particle scattering and track research, the subatomic world is revealing that it is composed of many different particles that form the current standard model: antimatter such as the positron, mediating particles such as photons and gluons, quarks that make up protons and neutrons. There are others that are theoretical, but physicists hope to find experimental evidence of them with the LHC. As theoretical physicists make new predictions, experimental physicists look for evidence to prove or disprove predictions. As new evidence is discovered, the theoretical physicists update theories and make new predictions, which the experimental physicists attempt to confirm in the never-ending circle of the scientific method.

Module Assessment

Question 1

Use the following information to answer this analytic question.

The Sun produces energy through nuclear fusion. In one particular reaction, energy is released when a hydrogen-2 nucleus fuses with a hydrogen-3 nucleus. This produces a helium-5 nucleus that is unstable and that decays to a helium-4 nucleus and a neutron. The fusion reaction chain is

$$^2_1\text{H} + ^3_1\text{H} \rightarrow ^5_2\text{He} \rightarrow ^1_0\text{n} + ^4_2\text{He}.$$
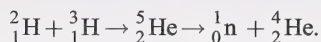
The masses of two of these particles are given in the following table.

Particle	Isotope Notation	Mass (10^{-27} kg)
Helium-4	^4_2He	6.64884
Neutron	^1_0n	1.67493

The decay of helium-5 to helium-4 and a neutron forms an isolated system. In this system, the mass defect is observed as an increase in kinetic energy.

A helium-5 nucleus, at rest, decays. Both the neutron and the helium-4 nucleus move away from the location of the decay. The helium-4 nucleus has a momentum of $1.903\,06 \times 10^{-20}$ N•s and a kinetic energy of $2.723\,50 \times 10^{-14}$ J.

- Determine the mass of a helium-5 nucleus.

Marks will be awarded based on the physics principles you provide, the formulas you state, the substitutions you show, and your final answer.

See the Analytic Scoring Guide in the appendix.

Question 2

Use the following information to answer the next question.

Radioactive isotopes (radioisotopes) are extremely important for some medical tests and procedures. A common radioisotope used for medical imaging is technetium-99. Technetium-99 is used because it releases 140 keV gamma rays that are easily detected outside of the body and doesn't damage surrounding tissue. It has a short half-life and the human body easily excretes its daughter products. The short half-life that makes it safe also means that the hospital needs a constant supply.

To solve this problem, scientists developed a technetium-99 generator from molybdenum-99, a by-product of spent nuclear reactor fuel. The molybdenum-99 needs replacing weekly instead of daily shipments of technetium-99. The generator starts with molybdenum-99, which decays into technetium-99, which can be separated by a relatively easy chemical process.

As a learning exercise, a medical student is asked to monitor the decay of a molybdenum-99 sample of 100 g over a week. The student measures the following values.

Time (h)	Mass Remaining (g)
0	100
10	90
20	81
30	73
40	66
50	59
60	53
70	48
80	43
90	39
100	35
110	31
120	28
130	26
140	23
150	21
160	19
170	17

- Graph the information.

- What is the half-life of molybdenum? Explain how you determined the half-life.

- What is the decay equation for molybdenum-99 into technetium-99?

- The decay of technetium-99 releases a 140 keV gamma ray. How much mass is changed into energy to create the gamma ray?

See the Graphing Scoring Guide in the appendix.
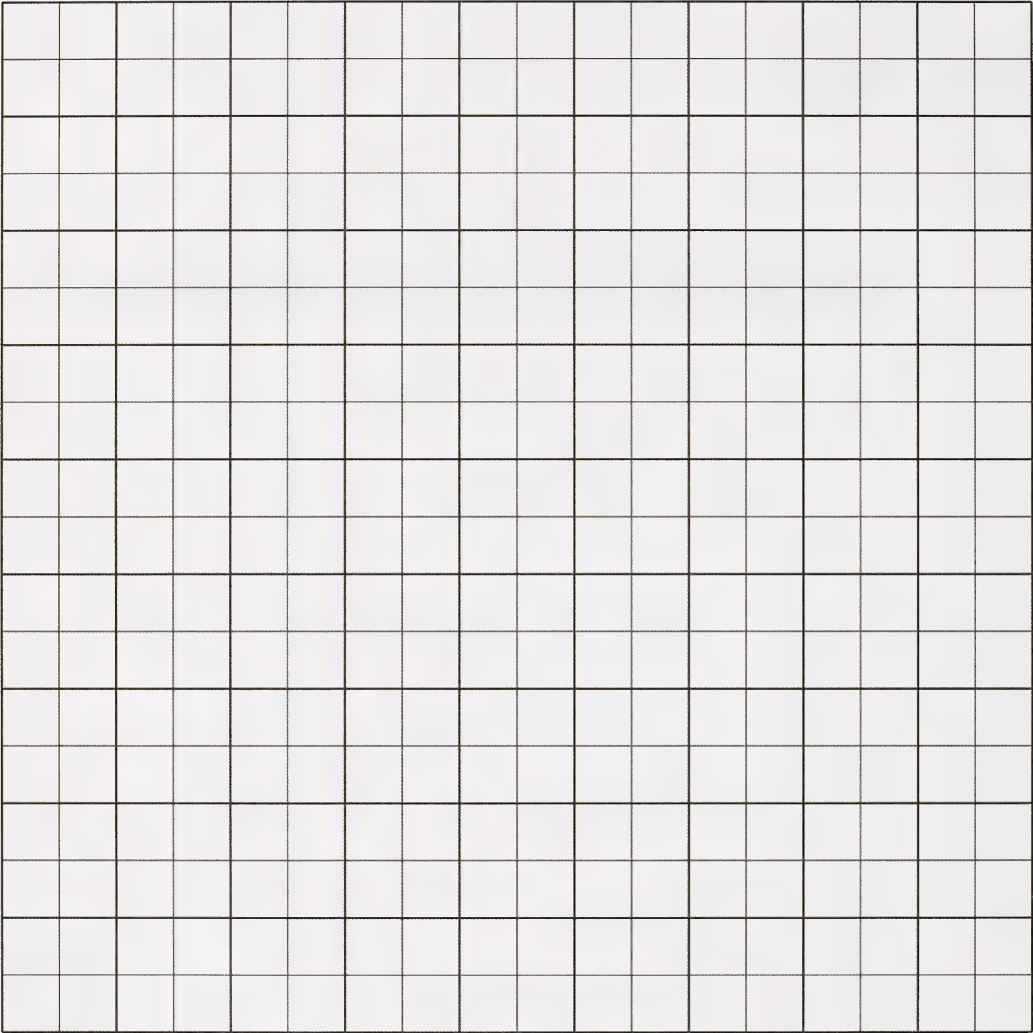
Module 8—Glossary

Module Glossary

activity or decay rate: the number of nuclei in a sample that decays in a given time interval

antimatter: a form of matter that has properties opposite to its normal-matter counterpart; an extension of the concept of normal matter that is made up of particles where antimatter is made up of antiparticles

All particles have an antiparticle.

antineutrino: a tiny subatomic particle with no charge emitted with $_{-1}^{0}e$ in beta decay

alpha particle: two protons and two neutrons bound together to form a stable particle identical to a helium nucleus

atomic mass: the weighted mean atomic mass number of the element's natural isotopes

This number is given on the periodic table.

atomic mass number (A): the number of nucleons in an atom's nucleus

atomic number (Z): the number of protons in the nucleus

The atomic number uniquely identifies the element.

becquerel (Bq): the unit of radioactivity equal to one decay per second

beta particle: an electron emitted by the nucleus when a neutron splits into a proton and electron during the beta decay process

binding energy: the net energy required to liberate all of the protons and neutrons in a nucleus (overcome the strong nuclear force)

bubble chamber: a device that tracks particles using bubbles in liquefied gas

CERN: Conseil Européen pour la Recherche Nucléaire (world's largest particle physics laboratory)

CERN had the first web server and posted the first page on the World Wide Web. See CERN's website to see that historic first page.

cloud chamber: a device that tracks particles using condensed gas vapours

daughter element: the element produced by a decay process

fission: when a nucleus with more than 120 nucleons splits into smaller nuclei with greater binding energy per nucleon

fundamental particle: a particle that cannot be divided into smaller particles; an elementary particle

fusion: when a nucleus with fewer than 60 nucleons combines with another to form a larger nucleus with greater binding energy per nucleon

gluon: a mediating particle for the strong nuclear force

graviton: a hypothetical mediating particle for the gravitational force

half-life: the time it takes for half the radioactive nuclei in a sample to decay

isotope: an atom that has the same number of protons but a different number of neutrons and, therefore, a different atomic mass number

mediating particle: a virtual particle that carries a fundamental force

nucleon: a proton or neutron

neutrino: a tiny subatomic particle with no charge emitted with a positron in beta-positive decay

neutron: a neutral particle found in the nucleus

parent element: the original element in a decay process

plasma: ionized gas in which the electrons have been separated from the nucleus

positron: the antimatter to an electron

It is the same type of particle but has an opposite charge. Unlike electrons, positrons are scarce.

proton: a positively charged particle found in all nuclei

quark: a fundamental particle in the hadron family

standard model: the current theory describing the nature of matter and the fundamental forces

transmutation: decay or change into a different element

virtual particle: a particle that exists for such a short time that it cannot be detected

$$u \rightarrow d + e^+ + v_e$$

$$d \rightarrow u + e^- + \bar{v}_e$$

Appendix

Discussion Scoring Guide

Discussion Scoring Guide

Principles involved: radiation, energy				
Criteria	Level 1 (Below Standard)	Level 2 (Approaching Standard)	Level 3 (Standard)	Level 4 (Above Standard)
Knowledge				
	Demonstrates a vague and sometimes incorrect understanding of the physics principles involved. Obvious irrelevant or missing information.	Demonstrates a basic understanding of the physics principles involved. May exhibit minor mistakes or vague information or application to the situation.	Demonstrates a good understanding of the physics principles involved and applies them properly to the given situation. All necessary information is given.	Demonstrates a superior understanding of the physics principles involved and their application to the situation. All applications are considered in detail.
Reflection				
The post shows reflection on one's own and other students' work. Contributes to the group discussion.	Does not make an effort to participate. Seems indifferent to discussion.	Occasionally makes meaningful reflections on the group's efforts or discussions. Marginal effort is shown to become involved with the group or discussion.	Frequently makes meaningful reflections on the group's efforts and presents relevant viewpoints for consideration by the group. Interacts freely with group members.	Regularly attempts to motivate the group discussion and delve deeper into concepts. Interacts freely and encourages all group members.
Content and presentation of discussion summary				

The information is logically arranged in a clear and concise manner.	The information is poorly organized with many concepts implied. Irrelevant or rambling sentences make reading difficult.	The information is somewhat organized with implied concepts. Excessive words or awkward sentences are used, which hinder reading.	The information is well-organized and logically arranged. All concepts are explicitly explained. There are a few awkward but understandable sentences.	The information is well-organized and very easy to understand. Well-worded sentences make reading pleasurable.

Analytic Scoring Guide

(5 marks each)
Check the following before you submit your work:

- Did you state the relevant physics principles as stated on your physics data sheet?
- Did you state the equation from the equation sheet?
- Did you show the manipulated form of the equation?
- Did you show the substitution and units?
- Did you calculate the correct final answer and paraphrase the answer with the correct significant digits and appropriate units?

Scoring Guide for Analytic Questions

Physics Principles

Score	Description
4	Both relevant physics principles are stated and both are clearly related to the response. Physics principles for questions involving linear vector addition require explicit communication of the vector nature; e.g., a situational diagram or a free-body diagram (FBD) for forces and a vector addition diagram.
3	Both relevant physics principles are stated, but only one is clearly related to the response.
2	Both relevant physics principles are stated but neither is clearly related to the response. **or** One relevant physics principle is stated and is clearly related to the response.
1	One relevant physics principle is stated.
0	No relevant physics principle is stated.

Substitutions

Score	Description
1	All substitutions are shown. Significant digits are not required in intermediate steps. A response with at most one implicit unit conversion may receive this score. An incomplete or incorrect response may receive this score if all the values substituted are appropriate; e.g., length measurements into length variables, energy measurements into energy variables.
0	Too many substitutions are missing. **or** The response contains one invalid substitution; e.g., electric field strength for energy or speed for electric potential difference.

Formulas

Score	Description
3	All relevant formulas required for the complete solution are present and have been written as they appear on the equations sheet or in the information given with the question.
2	Most relevant formulas are stated. **or** Derived formulas are used as starting points.
1	One relevant formula from the formula sheet is stated.
0	No relevant formula is stated.

Final Answer

Score	Description
2	The value of the answer to the complete problem is stated and calculated consistently with the solution presented. The final answer is stated with the appropriate number of significant digits and with appropriate units. A response in which an inappropriate substitution has been made may receive this score if the incorrect units are consistently carried forward.
1	The value of the final answer is stated, calculated consistently with the solution presented. Units or significant digits are incorrect. **or** The response is incomplete, but an intermediate value is stated and calculated consistently with the solution presented with appropriate units (significant digits not required).
0	The answer stated is unrelated to the solution shown. **or** No answer is given.

Graphing Scoring Guide

(5 marks)
Check the following before you submit your work:

- Did you put a title on the graph?
- Did you label each axis with an appropriate title including units?
- Are the axis scales appropriate to the size of the graph?
- Is the equation shown?
- Did you calculate the area and paraphrase the answer with the correct significant digits and appropriate units?

Scoring Guides for Graphing Skill-Based Questions—Mathematical Treatment

Score	Description
5	• All formulas are present. • All substitutions are given and are consistent with the graphed data. • The relationship between the slope, area, or intercept, and the appropriate physics is explicitly communicated. • The final answer is stated with appropriate significant digits and with appropriate units. Unit analysis is explicitly provided, if required. **Note:** one minor error may be present.*
4	• The response contains implicit treatment.** **or** • The response contains explicit treatment with up to three minor errors or one major error.***
3	• The response is incomplete but contains some valid progress toward answering the question; i.e., coordinates of relevant points are read correctly, including powers of 10 and units, and a valid substitution is shown.
2	• The coordinates of one relevant point are read. • The reason for requiring a point is addressed or implied.
1	• A valid start is present.
0	• Nothing appropriate to the mathematical treatment required is present.

*Minor errors include:

- Misreading a data value while interpolating or extrapolating up to one-half grid off.
- Stating the final answer with incorrect (but not disrespectful) units.

- Stating the final answer with incorrect (but not disrespectful) significant digits.
- Missing one of several different formulas.

**Implicit treatment means:

- Substituting appropriate values into a formula from the data sheets without stating the formula.
- Starting with memorized, derived formulas not given on the equations sheet.
- Substituting the value from one calculation into a second formula without communicating that the physics quantity in the two formulas is the same.

***Major errors include:

- Using off-line points (most often, this is calculating the slope using data points that are not on a linear line of best fit).
- Using a single data point ratio as the slope.
- Missing powers of 10 in interpolating or extrapolating.

Self-Check Answers

Contact your teacher if your answers vary significantly from the answers provided here.

Lesson 1

SC 1. According to the periodic table, the atomic number of lead is 82.

Given

$A = 204$
$Z = 82$

Required

neutron number (N)

Analysis and Solution

$N = A - Z$
$\quad = 204 - 82$
$\quad = 122$

Paraphrase

There are 122 neutrons in a nucleus of lead-204 or $^{204}_{82}\text{Pb}$.

SC 2. The weak nuclear force is involved in the transformation of a neutron into a proton and electron in beta-negative decay. In beta-positive decay, it would be involved in the transformation of a proton into a neutron and a positron.

SC 3.

a. $^{22}_{11}\text{Na} \rightarrow {}^{22}_{10}\text{Ne} + {}^{0}_{1}\beta + \bar{v}$
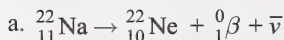
b. **Given**

masses

$^{22}_{11}\text{Na} = 21.994\,436 \text{ u}$

$^{22}_{10}\text{Ne} = 21.991385 \text{ u}$

$^{0}_{1}\beta = 5.485\,799 \times 10^{-4} \text{ u}$

$m_{\text{e}} = 5.485\,799 \times 10^{-4} \text{ u}$

Note: The sodium has 11 electrons but the neon has 10 electrons. One of the sodium's electrons drifts away during the decay but is not shown in the nuclear decay equation.

Required

The energy released by the beta-positive decay.

Analysis and Solution

Remember that there is an extra electron that must be taken into account in the final mass of the mass defect of a beta-positive, which is why the mass of the electron shows up twice: once for the beta-positive and once for the electron that drifts away.

Find the mass defect.

$$\Delta m = m_{\text{f}} - m_{\text{i}}$$
$$= \left({}^{22}_{10}Ne + {}^{0}_{1}\beta + m_{\text{e}}\right) - \left({}^{22}_{11}\text{Na}\right)$$
$$= \left(21.991\,385 \text{ u} + 5.485\,799 \times 10^{-4} \text{ u} + 5.485\,799 \times 10^{-4} \text{ u}\right) - \left(21.994\,436 \text{ u}\right)$$
$$= -0.001\,953\,840\,2 \text{ u}$$

The negative mass shows that it is lost as it is changed into energy.

Method 1: Energy in Joules

Convert the mass defect into kilograms (kg).

$$\text{mass defect} = 0.001\,953\,840\,2 \text{ u} \times \frac{1.66 \times 10^{-27} \text{ kg}}{1 \text{ u}}$$
$$= 3.243\,374\,7 \times 10^{-30} \text{ kg}$$

Find the energy.

$$E = mc^2$$
$$= \left(3.243\,374\,7 \times 10^{-30} \text{ kg}\right)\left(3.00 \times 10^8 \text{ m/s}\right)^2$$
$$= 2.919\,037\,3 \times 10^{-13} \text{ J}$$

Method 2: Energy in Electron Volts

From "Mass-energy Equivalence" on page 793 of your physics textbook,

$$E = 0.001\,953\,840\,2 \text{ u} \times \frac{931.5 \text{ MeV}}{1 \text{ u}}$$
$$= 1.82 \text{ MeV}$$

Warning: The value of 931.5 MeV/1u is **not** on the Physics Data Sheet for the Diploma Exam. To use this value you must derive it on the exam from values on the data sheet in order to receive full marks. Method 1 will be easier for the Diploma Exam.

Paraphrase

The energy released by the beta-positive decay is 2.92×10^{-13} J or 1.82 MeV.

Lesson 2

SC 1.

Given

$$t_{1/2} = 28 \text{ a}$$
$$N_0 = 60 \text{ g}$$
$$t = 84 \text{ a}$$

Note: a or y are acceptable units for years.

Required

the remaining amount of strontium-90 in 84 years

Analysis and Solution

Determine the number of half-lives in 84 years.

$$n = \frac{t}{t_{1/2}}$$
$$= \frac{84 \text{ a}}{28 \text{ a}}$$
$$= 3 \text{ half-lives}$$

Determine the remaining amount of strontium-90.

$$N = N_o \left(\frac{1}{2}\right)^n$$
$$= 60 \text{ g} \left(\frac{1}{2}\right)^3$$
$$= 7.5 \text{ g}$$

Paraphrase

The amount of strontium-90 remaining in the soil in 84 years is 7.5 g.

SC 2.

Given

$$t_{1/2} = 28 \text{ a}$$
$$N_o = 100 \text{ g}$$
$$t = 65 \text{ a}$$

Required

the remaining amount of strontium-90 in 65 years

Analysis and Solution

Determine the number of elapsed half-lives in 65 years.

$$n = \frac{t}{t_{1/2}}$$
$$= \frac{65 \text{ a}}{28 \text{ a}}$$
$$= 2.321\ 428\ 571 \text{ half lives}$$

Determine the amount of remaining strontium-90.

$$N = N_o \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$
$$= 100 \text{ g} \left(\frac{1}{2}\right)^{2.321\,428\,571}$$
$$= 21.538\,461\,54 \text{ g}$$

Paraphrase

The amount of strontium-90 remaining in the soil in 65 years is 21 g.

SC 3.

There are two ways of solving this question.

Method 1: How many ½ are there in ¼?

$$\frac{1}{4} = \frac{1}{2}^n$$
$$\frac{1}{4} = \frac{1}{2} \times \frac{1}{2}$$
$$\frac{1}{4} = \frac{1}{2}^2$$

Therefore, two half-lives have passed.

$$n = \frac{t}{t_{1/2}}$$
$$t = n t_{1/2}$$
$$= (2)(12.3 \text{ a})$$
$$= 24.6 \text{ a}$$

The elapsed time is 24.6 years.

Method 2: Logarithms

This method is optional. If you have seen logarithms in math class, you can use them here. In Physics 30 all questions like this should have whole-number answers for the number of half-lives.

$$N = N_o \left(\frac{1}{2} \right)^n$$

$$\frac{N}{N_0} = \left(\frac{1}{2} \right)^n$$

$$\log \left(\frac{N}{N_0} \right) = \log \left(\frac{1}{2} \right)^n$$

$$\log \left(\frac{N}{N_0} \right) = n \log \left(\frac{1}{2} \right)$$

$$n = \frac{\log \left(\dfrac{N}{N_0} \right)}{\log \left(\dfrac{1}{2} \right)}$$

$$n = \frac{\log \left(\dfrac{\frac{1}{4}}{1} \right)}{\log \left(\dfrac{1}{2} \right)}$$

$$n = 2$$

Determine the time for two half-lives.

$$n = \frac{t}{t_{1/2}}$$

$$t = n t_{1/2}$$

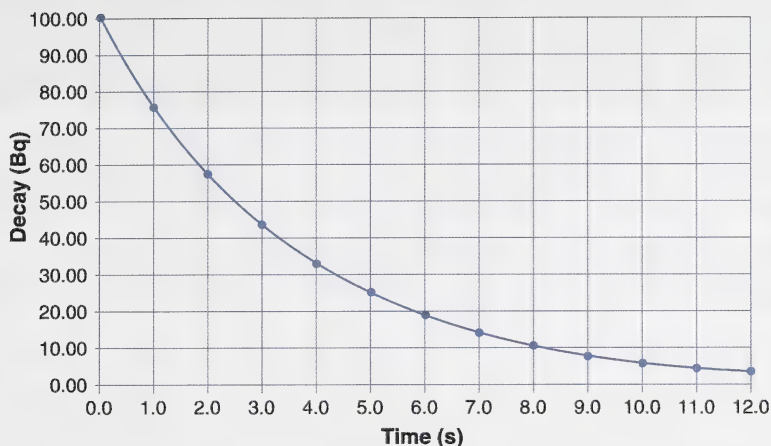$$= (2)(12.3 \text{ a})$$

$$= 24.6 \text{ a}$$

Paraphrase

The elapsed time is 24.6 years.

SC 4.

a. The independent variable is the time.

b. The dependent variable is the decays.

c.

Half-life Decay

d. The graphs shows an exponential relationship.

e. The half-life of the sample is 2.5 seconds. It is the time when the decays reach half the original value of 100. When the decays are 50, the time is 2.5 seconds.

f. After 17 seconds, there will be less than 1.0 Bq.

g. No, the decays will never reach zero; but for all practical purposes, after 5 half-lives, it is difficult to accurately measure the original amount. After 10 half-lives, the original radioactive atoms are considered completely transmuted. Less than 0.01% remains.

Lesson 4

SC 1.

Quarks		Leptons	
up	down	electron	electron-neutrino
charm	strange	muon	muon-neutrino
top	bottom	tau	tau-neutrino

SC 2. The four natural forces from weakest to strongest are as follows:

gravitational force – weakest
electromagnetic force
weak nuclear force
strong nuclear force - strongest

In Module 7 you studied the early works that led to the discovery of the cathode ray, which served as a vehicle for investigations into the nature of the particles that produced it. You also explored J.J. Thomson's work with the cathode ray, most importantly his determination of the charge-to-mass ratio of the particles in cathode rays, which was a ratio thousands of times larger than that for other common particles like the hydrogen ion. The concepts and theories used in Thomson's original experiment are now commonly applied in mass spectrometer technology.

By showing that cathode rays were deflected by electric and magnetic fields, Thomson proved that they were streams of negatively charged elementary particles—the electrons. He then developed the "raisin-bun model" of the atom, which featured electrons plopped into a bread of positively charged matter. Millikan's now-famous oil drop experiment determined the actual charge of that particle. It also confirmed that the atom was divisible into smaller parts.

Rutherford's scattering experiment further developed the atomic model. A high percentage of the large positive particles directed at the thin foil passed through the foil, indicating that the atom was mostly empty space (and not a bun). Some particles, however, were deflected. Rutherford concluded that the atom included a small, positively charged region that could deflect the incoming particles by electrostatic repulsion. His discoveries lead to the planetary model of the atom.

The planetary model presented some difficulty with classical physics and required significant revisions, which were accomplished courtesy of Niels Bohr. Bohr recognized that, according to Maxwell's theory, if electrons (which are charged particles) are experiencing centripetal acceleration, these accelerating particles should continuously emit electromagnetic radiation (EMR). According to conservation of energy, however, this emission of energy should result in a decrease in the electron's kinetic energy and its eventual spiral into the nucleus.

Bohr's Semi-Classical Model describes electrons orbiting the nucleus in certain stable states (energy levels) with specific energies and radii. This quantization of the energy explained patterns in the EMR spectrum of certain elements leading to the identification of atoms and elements on distant objects, such as the Sun.

Finally, you explored the Quantum Mechanical Model of the atom, which described the electron position using a probability distribution—a distribution that indicates where the electron is most likely to be found at any given time.

Studying all of these theories about the composition and structure of the atom in Module 7 helped you understand that theories are constantly changing and that scientific models are human inventions created to try to understand and explain physical phenomena. As science continues to uncover secrets of the atom, new models will evolve. This is very important to remember as we try to explain things we cannot see in Module 8.

In Module 8 you explored how an ionizing smoke detector depends on the unstable americium-241 nucleus in order to detect smoke and save lives. Since some nuclei are unstable, they can decay, resulting in different elements. This natural change from one element to another is called transmutation, and it can produce alpha and beta particles.

You learned how both alpha and beta decay produce significant amounts of energy observed in the kinetic energy of the emitted particles and the production of high-frequency gamma radiation, both of which can ionize gas in a smoke detector when smoke particles are absent.

Next, you investigated how the unstable nuclei decays and how the amount of radioactivity emitted reduces over time. The rate of decay is described by the half-life of the radioactive isotope. You then learned how it is possible to accurately determine the age of a sample, given the half-life of the radioactive isotope, the remaining amount of parent nuclei, and the original amount of the parent nuclei.

You then explored fission and fusion, which are also very powerful. You discovered that both fission and fusion nuclear reactions are processes that lead to an increase in the binding energy per nucleon, increasing the stability of the resulting nuclei. In both cases, the total, final binding energy is much larger than the initial binding energy, producing a more stable nucleus and releasing a large amount of energy that can power modern civilization.

You then compared the product of hydrogen fusion (helium), which is stable and safe, to the unstable, dangerous daughter nuclei produced in a fission reaction. Both reactions, however, have positive and negative aspects.

Next, you learned about particle accelerators and how they are being used to create collisions at energies never before seen on Earth. From these collisions the content of the particles can be probed and studied, which is very exciting to the world of subatomic physics.

Lastly, you explored the subatomic world and the standard model and discovered it is composed of strange ideas and particles (some that still need to be verified!), such as antimatter, mediating particles, and the quarks that make up protons and neutrons. You learned that the standard model changes as more evidence is collected and that the interaction of theory and observation lead to more discoveries. Together, they both work toward a grand unified theory that will connect the fundamental forces of the universe and the particles that mediate, create, and sustain them.

Unit D Assessment

There is no unit-level assessment. In each module you completed a significant number of assessment activities. Some activities were assessed by you (e.g. Self-Check) or your classmates (e.g. Discuss) and others were assessed by your teacher (e.g. Lesson Assignment, Portfolio Assessment, Discussion Assessment, and Module Assignment).

Course Conclusion

Congratulations, you have completed Physics 30!

Contact your teacher to determine if there will be a final test or any additional assessment for you to complete.